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U. S. DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU.
BULLETIN F.

VERTICAL GRADIENTS
OF
TEMPERATURE, HUMIDITY, AND WIND DIRECTION.

A PRELIMINARY REPORT ON THE KITE OBSERVATIONS OF 1898.

PREPARED UNDER DIRECTION OF WILLIS L. MOORE, CHIEF U. S. WEATHER BUREAU,
BY
H. C. FRANKENFIELD, Forecast Official.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
1899.

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From the
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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture,
Weather Bureau, Office of the Chief,
Washington, D. C.

Hon. James Wilson,
Secretary of Agriculture.

Sir: I have the honor to transmit for publication, herewith, a paper on Vertical Gradients of Temperature, Humidity, and Wind Direction, being a preliminary report on the kite observations of the year 1898, by Dr. H. C. Frankenfield, forecast official.

Dr. Frankenfield states that in the preparation of this paper he has freely consulted with Professors Abbe, Bigelow, and Marvin, of this Bureau. An introductory chapter on the Kite Meteorograph, Construction, and Operation is added by Prof. C. F. Marvin.

This report discusses probably the largest amount of free-air meteorological observations ever taken within a like space of time over so great an area, and I believe will be found to have added something to the general knowledge of temperature and hygrometric conditions of the lower levels of the air.

Very respectfully,

Willis L. Moore,
Chief United States Weather Bureau.

Approved:
James Wilson,
Secretary of Agriculture.

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KITE METEOROGRAPH, CONSTRUCTION, AND OPERATION.

By Prof. C. F. Marvin.

In designing the kites, meteorograph, and aerial apparatus employed in making the observations discussed in the accompanying paper, it was necessary to satisfy a number of conditions and limitations, as, for example, portability, simplicity, and strength of construction, especially as regards the kite; uniformity and interchangeability not only of parts of the apparatus, but of parts of the same devices, so that repairs and renewals could be made as easily as possible. The corps of observers, moreover, when they began, were without previous experience in kite flying. The entire class, however, reported at Washington before the individual members were assigned to station, and was put through a preliminary drill and course of instruction in the practical work. In the short period of ten to twenty days devoted to this instruction (including the time lost during unfavorable weather) it was possible for the observers to gather only a general knowledge of the apparatus and methods of work.

The kite.—In conformity with the foregoing limitations, it was considered best to employ in each ascension only one kite, rather than several in tandem, which latter are very troublesome to set flying in light and fitful winds and are not required; in fact, are less efficient than a single kite in favorable winds.

Nearly all observations were made with a medium size kite containing 68 square feet of supporting surface. At some stations a smaller and a slightly larger kite were also sometimes used, according to the strength of the wind. The smaller size contained 45 square feet and the larger 72 square feet. Fig. 1 shows the kite with the meteorograph in place. The dimensions of the medium size kite are as follows:

Transverse width of kite	6 feet 6 inches.
Length, over extreme edges, fore and aft[1]	6 feet 2½ inches.
Distance between top and bottom supporting surfaces	2 feet 8 inches.
Width of cloth bands	2 feet.

These kites are framed and constructed in the most rigid manner possible. The six longitudinal sticks running fore and aft are attached by means of small machine screw bolts to the rectangular frames forming the rigid edges to the cloth bands and are detachable; thus permitting the kite to be collapsed, as shown in fig. 2.

The best cloth material for kites seems to be Lonsdale cambric, which is light, strong, and closely woven. A black, or dark-colored cloth is more visible on many occasions, and the rear cell was covered with black nainsook on this account. This cloth is not as strong as the cambric, but, owing to the circumstance that the pressure per unit area on kites of this type is very much greater in the forward than in the rear cell, the above disposition of the relatively strong and weak material is wholly justified. This same circumstance explains why the front cell is made with three supporting surfaces, as compared with two in the rear cell; that is to say, this increase of surface (at slight increase of weight) increases the lifting efficiency of the kite.

---

[1] The length, fore and aft, was increased to 6 feet 8½ inches, in later forms.

The flying line is attached to the front edge of the forward cell at the middle; the ordinary arrangement of this connection being more fully shown in fig. 3.

Bridle and safety line.—The normal bridle, including the safety line for the kite, is shown in fig. 3. The cord (No. 32 Italian blocking cord) at *A* is passed twice around the stick, after the fashion of a "clove hitch;" the free portions of the line, one of which is rather short, are firmly bound together where they emerge from the clove hitch by a serving of waxed "gilling" thread. The long end is passed through one of the metal safety-line eyes, *B*, and the two ends tied together by means of bowline knots, as at *b*. A similar, but longer, piece of cord is secured at *C* by a clove hitch and the free ends attached to each other by bowline knots after the long end has been passed through the eye *B′*. When *B′* is held so that the line *AB′* is taut and at an angle of 90° to the stick, the line *C′B* should be just a little taut. The main line is attached to the bridle at *B′*.

Safety line.—The eyes, *BB′*, are connected by what is termed a safety line, *S*, which is simply a piece of steel wire, the size of which is so chosen that its ultimate strength is within a safe working strain for the kite and flying line. In normal flight all the strain produced by the kite upon the line is transmitted through the safety line *S*. If in any case the conditions give rise to a greater strain than the ultimate strength of the safety line (and therefore dangerous to either the kite or the line, or both), it will be broken. In this case the kite will thereafter fly from the point *C*, which is several inches in advance of *A*. Such a change in the bridle causes a diminished pull by the kite, other things being the same.

The safety lines generally supplied have a tensile strength of about 85 pounds.

The reel.—The management of large kites in flight requires a substantial and convenient form of reel of the character indicated in fig. 4. The top portion of the carriage revolves upon the table below on bearings resembling the so-called "fifth wheel" of wagons. The drum revolves easily in metal bearings and is fitted with dials at the axle indicating the number of revolutions. At the start the dials stand at zero and count off revolutions as the wire unwinds.

Strap brake.—The lever seen at the right in fig. 4 operates a powerful strap-iron friction brake acting on the rim of the drum and controls in the easiest and most complete manner the unwinding of the wire or the stoppage of the reel under all circumstances.

A matter of great importance in the design of the winding drum of the reel is to secure sufficient strength in the rim to withstand the enormous cumulative pressure exerted by a large amount of wire wound in under great tension. A single turn of wire around the drum, under a uniform strain of 50 pounds, for example, tends to produce a compressive stress of 50 pounds at every point around the rim. The next turn, at the same tension, adds 50 pounds to the preceding stress, and so on. Two thousand turns at this rate will, therefore, produce a pressure of 100,000 pounds, or 500 tons. The heavy rim of the cast-iron drum, shown in fig. 4, is calculated to safely resist a crushing pressure of fully 1,000 tons. In actual practice the crushing pressure is not quite so great as that calculated by the process indicated above, because the material of the reel yields a little as the pressure increases, and this lessens the tension on the turns of wire already wound on the drum. The side flanges of the drum must also be very strong, as the wire crowds sidewise against these with great force. It is best on this account not to wind the wire on in smooth and even layers, but rather to crisscross the turns of wire slightly, but in a regular manner. Wound in this way, the wire tends to support itself, even without side flanges; at any rate, the lateral pressure is greatly reduced, and, moreover, the outside turns of wire are not able to squeeze down through what is already wound on the reel, as they tend to do when the wire is wound in an even manner, like thread on a spool.

When flying at an elevation of from 5,000 to 7,000 feet, one of the Weather Bureau kites, supporting its instrument, will pull from 60 to 80 pounds, if not more, and from 8,000 to 10,000 feet of wire will be out. To wind all this wire in under such conditions is really a very laborious operation, and generally requires two men at pretty hard work for from a half to three-quarters of an hour or more.

As sent out to stations the hand reels contained from 2,600 to 3,000 turns of tempered steel music wire, 0.028 of an inch in diameter. The normal tensile strength of this wire was about 200 pounds.

Length of wire.—As the original supply of wire was wound upon each reel, record was kept of the total number of turns and a table computed, giving the number of turns corresponding to given lengths of wire in units of 500 feet. Due account is taken in these tables of the gradual diminution in the length of each turn as more and more wire is unwound. The coefficient of diminution was determined from several sets of readings of the revolutions of a measuring wheel around which the wire passed as it was being wound on a reel. Simultaneous readings of the dial on the reel were also made. The measuring wheel was accurately 3 feet in circumference and the dial indicated feet.

Electrical connections.—The wire line employed in flying kites becomes electrified more or less at all times, often highly so. For comfort of the operators, as well as safety, this charge must be conveyed to earth, and for this purpose each reel stand is provided with an electric ground-connection and switch. The 15-inch cranks by which the reel is revolved are made of wood for the sake of insulation.

Radius rod and arc.—It is important to know the inclination of the wire at the reel in order to make a proper allowance for the sag of the wire. This is accomplished by means of the radius rod and the graduated arc, fig. 4. The radius rod is clasped loosely upon the axle of the reel on either side of the drum, and the arc hung over the shaft on a pair of antifriction wheels which run in a groove turned in the shaft. A weighted rod below the arc causes it to maintain a vertical position at all times, thus insuring correct angles. In use, the radius rod is made to rest against the wire, the angular inclination of which to the horizontal is then shown by the reading upon the graduated arc. This angle is subject to a small and variable inaccuracy, due to slight alterations in the radial distance of the wire at the point it leaves the drum, according as more or less of the wire is unwound.

Dynamometer.—The tension upon the line at the reel at any time is determined by means of the dynamometer permanently attached to one of the crank handles, as seen in fig. 4. This consists of a short, stiff, steel spring, firmly fastened to the outer end of the handle at the back. The short end of a multiplying lever connects with the spring, while the long end serves as an index and traverses the graduated arc shown on the crank handle near the axis. The reading on this graduated arc indicates the pull in pounds on the wire. Here, likewise, a small and variable error is introduced because of the variations in the diameter of the drum with different amounts of wire out. This is not important.

End of wire.—The outer end of the wire terminates in a small brass eye. To facilitate connecting the wire to the kite, a piece of No. 32 blocking cord about 8 feet long is fastened to the eye—that is to say, the cord is simply passed through the eye and a bowline knot tied on one end.

Reel box, cover, and lock.—When not in use it is designed simply to inclose the reel within the box by means of a suitable cover. The crank handles are unshipped and placed inside the box. The cover is secured and locked by means of an eyebar, which passes between the spokes of the drum and is fastened by a padlock on one end.

The meteorograph.—The instrument sent up with the kite to secure the automatic record of the conditions of the air is seen in fig. 1 as it appears attached to the kite and inclosed within its light aluminum case. The mechanisms inside the case are shown in fig. 5, and are designed to record wind velocity, temperature, pressure, and humidity of the air. Records of the velocity of the wind were, however, made experimentally only at Washington, and were not included in the official observations.

Special consideration was given in designing the meteorograph to secure a proper exposure of the hair hygrometer and the thermograph bulb. The former consists of a strand of prepared hairs stretched back and forth in a double strand and nearly from end to end inside the long tube seen at the top portion of the instrument, as shown in fig. 5. The direct elongation and contraction of these hairs is communicated to the recording pen at the extreme right side in fig. 5. The thermograph bulb is also placed within the long tube and occupies nearly a middle position.

When attached to the kite, as shown in fig. 1, the meteorograph is so placed that the wind blows with full force directly through the tube containing the thermometer bulb and hygrometer, thus affording thorough and complete ventilation, radiation being at the same time effectually cut off. Even though the metallic case of the instrument becomes heated on exposure to sunshine, yet the metal tube itself is not only shaded and exposed to a strong current of wind, but is everywhere separated from contact with the metallic case by vulcanite rings at the ends and longitudinal ivory strips on the sides. Indeed, celluloid strips are interposed between the thermometer bulbs and the metal of the inclosing tube, thereby still further insulating the thermometer bulbs. These bulbs consist of a pair of tempered-steel bourdon pressure tubes, forming a curl of about seven-eighths of a complete circle about 1½ inches in diameter. The major and minor axes of the elliptical cross section of the tubes measure approximately 0.5 and 0.1 of an inch, respectively. The tubes are filled with pure alcohol under pressure, and are set in tandem and edgewise to the current of wind through the tube. Thus arranged, they constitute highly sensitive and relatively powerful thermometric bulbs. The recording pen traverses a scale of 22 degrees to the inch, each instrument being adjusted to this scale by tests at different temperatures, the air being driven through the tube by means of an electric fan. The record sheet provides a range of 45 degrees possible change of temperature in any ascension, the initial setting of the thermograph pen being effected by a suitable adjusting screw.

The mechanism of the aneroid barometer is readily understood from fig. 5. The novel feature in this part of the meteorograph consists in the use of tempered and highly elastic steel corrugated disks, instead of brass or German silver ordinarily used. Numerous tests showed the steel vacuum chambers to be superior to others. Nevertheless the aneroid principle has not thus far proved to give pressure records characterized by that high degree of precision required in meteorological work.

The pressure scale on the record sheet embraces a range of 9 inches, viz, 21 to 30 inches air pressure. The subdivisions of the sheet are 22 spaces per inch, each space representing 0.2 of an inch barometric pressure.

It will be noticed these spaces are the same as the degree spaces on the temperature record. This arrangement was chosen so that in extreme cases the temperature record might overlap on the space normally provided for pressure, and vice versa, and still be properly scaled by the rulings on the sheet. Furthermore, in designing the instrument the scales were so chosen that in an ascension under average atmospheric conditions the pressure and temperature curves would have about the same actual amplitude. Hence the change of temperature in a given elevation is measured with the same accuracy as the corresponding change in pressure, at least so far as the traces themselves are concerned. A greater precision of pressure measurement is desirable, but is scarcely justified by the inherent defects of the aneroid principle of measurement.

Each recording pen is adjustable, and at or before the time of ascension the pens are set as nearly as may be to indicate correctly the atmospheric conditions as shown by readings of the sling psychrometer and mercurial barometer. After these settings are made and just before ascensions, the meteorograph having been exposed for some time in the wind, readings of the psychrometer and barometer are again made and the outstanding differences of the indications of the meteorograph noted and used as corrections to the automatic records, similar corrections being noted at the close of the ascension.

Elevation of the kite.—The vertical height of the kite and hence the meteorograph above ground was determined from readings of the angular elevation of the kite, the length of line out, and its inclination at the reel. The angular elevation was measured to the nearest half degree by means of the nephoscope, shown in fig. 6. The position of the sighting staff also indicated the angular azimuth of the kite.

The approximate elevation of the kite was taken out from a table giving values of the expression $h = l \sin \varphi$. A percentage correction was then applied, depending upon the amount of sag in the wire as shown by its observed inclination at the reel.

Table I gives the percentage of slack in the wire, as deduced from the equation of the catenary for such conditions as commonly occur.

Table II is a copy of one of the cards furnished with reel No. 15, giving the number of turns of the reel corresponding to the lengths of wire out in 500-foot intervals.

As a rule, observations were made with whole units of 500 feet of wire out, so that interpolation was not necessary. The length of wire in one turn was, however, accurately tabulated, and facilitated accurate interpolation.

TABLE I.—ANGULAR ELEVATION AND PERCENTAGE OF SLACK.

Angular elevation of kite.	Inclination of wire at reel.																Angular elevation of kite.
	0°	5°	10°	12°	14°	16°	18°	20°	22°	24°	26°	28°	30°	35°	40°	45°	
	Percentage of slack.																
o																	o
24	2.4	1.6	0.9	0.7	0.5												24
26	2.7	1.8	1.1	0.9	0.7	0.5											26
28	3.1	2.2	1.4	1.1	0.9	0.7	0.5	0.3									28
30	3.4	2.5	1.6	1.3	1.1	0.9	0.7	0.5	0.3								30
32	3.7	2.8	1.9	1.6	1.3	1.1	0.8	0.6	0.4	0.3							32
34	4.1	3.1	2.2	1.9	1.6	1.3	1.0	0.8	0.6	0.4	0.3	0.1	0.0				34
36	4.4	3.4	2.5	2.2	1.8	1.5	1.2	1.0	0.8	0.6	0.4	0.2	0.1				36
38	4.6	3.6	2.7	2.4	2.1	1.8	1.5	1.2	1.0	0.8	0.6	0.4	0.3				38
40	4.9	3.9	3.0	2.7	2.4	2.1	1.8	1.5	1.2	1.0	0.8	0.6	0.4	0.2			40
42	5.1	4.2	3.3	3.0	2.6	2.3	2.0	1.7	1.4	1.2	1.0	0.8	0.6	0.3			42
44	5.3	4.4	3.5	3.2	2.8	2.5	2.2	1.9	1.6	1.4	1.2	1.0	0.8	0.4	0.1		44
46	5.5	4.6	3.7	3.4	3.1	2.8	2.5	2.2	1.9	1.6	1.4	1.1	0.9	0.5	0.2		46
48	5.7	4.8	3.9	3.6	3.3	3.0	2.7	2.4	2.1	1.8	1.6	1.3	1.1	0.6	0.3	0.0	48
50	5.9	5.0	4.1	3.8	3.5	3.2	2.9	2.6	2.3	2.0	1.8	1.5	1.3	0.8	0.4	0.1	50
52			4.3	4.0	3.7	3.4	3.1	2.8	2.5	2.2	2.0	1.7	1.5	0.9	0.5	0.2	52
54								2.9	2.6	2.4	2.1	1.9	1.7	1.1	0.7	0.3	54
56													1.8	1.3	0.8	0.4	56

TABLE II.—SHOWING LENGTH OF WIRE UNWOUND FROM KITE REEL.

REEL No. 15.

Wire out.	Dial reading.	Length of one turn.
Feet.		*Feet.*
0	0	5.03
500	100	5.02
1,000	199	5.01
1,500	299	5.00
2,000	400	4.98
2,500	500	4.97
3,000	601	4.96
3,500	702	4.95
4,000	803	4.94
4,500	904	4.93
5,000	1,005	4.92
5,500	1,107	4.91
6,000	1,209	4.90
6,500	1,311	4.89
7,000	1,413	4.88
7,500	1,516	4.87
8,000	1,619	4.86
8,500	1,722	4.85
9,000	1,825	4.84
9,500	1,929	4.83
10,000	2,032	4.81
10,500	2,136	4.80
11,000	2,240	4.79
11,500	2,345	4.78
12,000	2,449	4.77
12,500	2,554	4.76
13,000	2,660	4.75
13,500	2,765	4.74
14,000	2,871	4.73
14,357	2,946	4.72

INSTRUCTIONS FOR USE OF TABLE SHOWING LENGTH OF WIRE UNWOUND FROM KITE REEL.

The table has been arranged to show dial readings corresponding to even lengths of 500 feet.

If the length of wire out is desired for a dial reading intermediate to those given in the table it can be determined by multiplying the difference between the *observed dial reading* and the nearest *tabulated dial reading* by the corresponding *length of one turn* of wire as given in the third column of table. The product should be added to or subtracted from the length in the first column opposite the tabulated dial reading used, according to whether the observed dial reading is greater or less than the tabulated dial reading. Example:

The observed dial reading is.......................... 2,000
The nearest tabulated dial reading is 2,032
The difference is 32
The corresponding length of one turn is................ 4.82

$$4.82 \times 32 = 154$$

$$10,000 - 154 = 9,846$$

which is the length of wire out corresponding to the observed dial reading.

WILLIS L. MOORE,
Chief of Bureau.

For further particulars concerning the details of the aerial apparatus employed in the Weather Bureau work and data concerning the efficiency of kites, the reader is referred to the Monthly Weather Review, Vol. XXIV, 1896, p. 113; Vol. XXV, 1897, p. 136; Yearbook of the Department of Agriculture for 1898, p. 201, and "Instructions for Aerial Observers," 1898, W. B. No. 166.

VERTICAL GRADIENTS OF TEMPERATURE, HUMIDITY, AND WIND DIRECTION.

A PRELIMINARY REPORT ON THE KITE OBSERVATIONS OF 1898.

INTRODUCTORY.

Kite ascensions were commenced at seventeen stations during the latter portion of the month of April and were continued into the early days of November, 1898, but in the preparation of this report only those from May to October, inclusive, have been considered.

Ascensions were made on every day when it was possible to do so. For obvious reasons the kites could not be flown in rainy or extremely threatening weather, and a considerable number of days was lost on this account. The principal reason, however, for failures to obtain satisfactory ascensions daily was the absence of a sufficient wind velocity to sustain the kites. There were made 44 per cent of the total number of ascensions which would have been possible had the wind and weather conditions been favorable. The percentage of ascensions at the different stations varied from 75 at Dodge City, Kans., where the wind velocity was greatest, to 12 at Knoxville, Tenn., where it was least. The largest number of ascensions was obtained in the country west of the Mississippi River, and the least in the central river valleys.

The temperature conditions at all elevations and under varying conditions of weather and time have been computed in terms of the gradient in degrees Fahrenheit for each 1,000 feet, and in the increase of elevation necessary to cause a fall of 1 degree in the temperature. The mean results, however, are given only in degrees per thousand feet.

Some attention has also been given to the questions of wind directions, relative humidity, and vapor pressure.

The tables and plates accompanying will, it is believed, furnish all the tabular matter that may be desired.

SUMMARY OF OBSERVATIONS.

Stations.	Elevation above sea level.	Number of months observations.	Number of ascensions.	Number of observations at—									
				1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Total.
	Feet.												
Washington, D. C	115	5.0	87	51	52	53	28	19	9	7	3	1	223
Cairo, Ill	315	5.5	39	6	33	31	23	19	4	.....	.....	.....	116
Cincinnati, Ohio	940	5.0	38	3	7	24	19	16	9	3	.....	.....	81
Fort Smith, Ark	[1] 527	5.0	19	12	18	18	8	2	.....	.....	.....	.....	58
Knoxville, Tenn	990	5.0	19	8	8	8	8	2	.....	.....	.....	.....	34
Memphis, Tenn	319	4.3	37	16	22	27	26	21	5	.....	.....	.....	117
Springfield, Ill	684	5.0	46	15	52	53	28	15	9	2	.....	.....	174
Cleveland, Ohio	705	5.0	93	29	62	55	48	21	11	1	.....	.....	227
Duluth, Minn	1,197	5.5	96	61	71	83	60	32	13	5	.....	.....	325
Lansing, Mich	869	5.0	58	23	23	22	34	22	10	.....	.....	.....	134
Sault Ste. Marie, Mich	722	5.3	74	7	42	46	39	31	15	.....	.....	.....	180
Dodge City, Kans	2,473	6.0	138	119	123	118	106	66	28	10	2	1	573
Dubuque, Iowa	894	5.7	65	19	32	40	35	15	7	.....	.....	.....	148
North Platte, Nebr	2,811	6.0	132	70	162	133	102	44	13	1	.....	.....	525
Omaha, Nebr	1,241	4.5	61	0	29	50	45	34	19	6	2	.....	185
Pierre, S. Dak	1,595	5.5	134	96	105	91	65	38	19	2	.....	.....	416
Topeka, Kans	972	6.0	81	68	65	76	72	26	11	1	.....	.....	319
Total	....	....	1,217	603	906	928	746	423	182	38	7	2	3,835

[1] 516 after July 31.

TABLE FOR THE CONVERSION OF RATES INTO GRADIENTS.

Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Feet.	°	*Feet.*	°	*Feet.*	°	*Feet.*	°	*Feet.*	°
100	10.00	176	5.68	252	3.97	328	3.05	404	2.48
101	9.90	177	5.65	253	3.95	329	3.04	405	2.47
102	9.80	178	5.62	254	3.94	330	3.03	406	2.46
103	9.71	179	5.59	255	3.92	331	3.02	407	2.46
104	9.62	180	5.56	256	3.91	332	3.01	408	2.45
105	9.52	181	5.52	257	3.89	333	3.00	409	2.44
106	9.43	182	5.49	258	3.88	334	2.99	410	2.44
107	9.35	183	5.46	259	3.86	335	2.99	411	2.43
108	9.26	184	5.43	260	3.85	336	2.98	412	2.43
109	9.17	185	5.41	261	3.83	337	2.97	413	2.42
110	9.09	186	5.38	262	3.82	338	2.96	414	2.42
111	9.01	187	5.35	263	3.80	339	2.95	415	2.41
112	8.93	188	5.32	264	3.79	340	2.94	416	2.40
113	8.85	189	5.29	265	3.77	341	2.93	417	2.40
114	8.77	190	5.26	266	3.76	342	2.92	418	2.39
115	8.70	191	5.24	267	3.75	343	2.92	419	2.39
116	8.62	192	5.21	268	3.73	344	2.91	420	2.38
117	8.55	193	5.18	269	3.72	345	2.90	421	2.38
118	8.47	194	5.15	270	3.70	346	2.89	422	2.37
119	8.40	195	5.13	271	3.69	347	2.88	423	2.36
120	8.33	196	5.10	272	3.68	348	2.87	424	2.36
121	8.26	197	5.08	273	3.66	349	2.87	425	2.35
122	8.20	198	5.05	274	3.65	350	2.86	426	2.35
123	8.13	199	5.03	275	3.64	351	2.85	427	2.34
124	8.06	200	5.00	276	3.62	352	2.84	428	2.34
125	8,00	201	4.98	277	3.61	353	2.83	429	2.33
126	7.94	202	4.95	278	3.60	354	2.82	430	2.33
127	7.87	203	4.93	279	3.58	355	2.82	431	2.32
128	7.81	204	4.90	280	3.57	356	2.81	432	2.31
129	7.75	205	4.88	281	3.56	357	2.80	433	2 31
130	7.69	206	4.85	282	3.55	358	2.79	434	2.30
131	7.63	207	4.83	283	3.53	359	2.79	435	2.30
132	7.58	208	4.81	284	3.52	360	2.78	436	2.29
133	7.52	209	4.78	285	3.51	361	2.77	437	2.29
134	7.46	210	4.76	286	3.50	362	2.76	438	2.28
135	7.41	211	4.74	287	3.48	363	2.75	439	2.28
136	7.35	212	4.72	288	3.47	364	2.75	440	2.27
137	7.30	213	4.69	289	3.46	365	2.74	441	2.27
138	7.25	214	4.67	290	3.45	366	2.73	442	2.26
139	7.19	215	4.65	291	3.44	367	2.72	443	2.26
140	7.14	216	4.63	292	3.42	368	2.72	444	2.25
141	7.09	217	4.61	293	3.41	369	2.71	445	2.25
142	7.04	218	4.59	294	3.40	370	2.70	446	2.24
143	6.99	219	4.57	295	3.39	371	2.70	447	2.24
144	6.94	220	4.55	296	3.38	372	2.69	448	2.23
145	6.90	221	4.52	297	3.37	373	2.68	449	2.23
146	6.85	222	4.50	298	3.36	374	2.67	450	2.22
147	6.80	223	4.48	299	3.34	375	2.67	451	2.22
148	6.76	224	4.46	300	3.33	376	2.66	452	2.21
149	6.71	225	4.44	301	3.32	377	2.65	453	2.21
150	6.67	226	4.42	302	3.31	378	2.65	454	2.20
151	6.62	227	4.41	303	3.30	379	2.64	455	2.20
152	6.58	228	4.39	304	3.29	380	2.63	456	2.19
153	6.54	229	4.37	305	3.28	381	2.62	457	2.19
154	6.49	230	4.35	306	3.27	382	2.62	458	2.18
155	6.45	231	4.33	307	3.26	383	2.61	459	2.18
156	6.41	232	4.31	308	3.25	384	2.60	460	2.17
157	6.37	233	4.29	309	3.24	385	2.60	461	2.17
158	6.33	234	4.27	310	3.22	386	2.59	462	2.16
159	6.29	235	4.26	311	3.22	387	2.58	463	2.16
160	6.25	236	4.24	312	3.21	388	2.58	464	2.16
161	6.21	237	4.22	313	3.19	389	2.57	465	2.15
162	6.17	238	4.20	314	3.18	390	2.56	466	2.15
163	6.13	239	4.18	315	3.17	391	2.56	467	2.14
164	6.10	240	4.17	316	3.16	392	2.55	468	2.14
165	6.06	241	4.15	317	3.15	393	2.54	469	2.13
166	6.02	242	4.13	318	3.14	394	2.54	470	2.13
167	5.99	243	4.12	319	3.13	695	2.53	471	2.12
168	5.95	244	4.10	320	3.12	396	2.52	472	2.12
169	5.92	245	4.08	321	3.11	397	2.52	473	2.11
170	5.88	246	4.07	322	3.10	398	2.51	474	2.11
171	5.84	247	4.05	323	3.10	399	2.51	475	2.11
172	5.81	248	4.03	324	3.09	400	2.50	476	2.10
173	5.78	249	4.02	325	3.08	401	2.49	477	2.10
174	5.75	250	4.00	326	3.07	402	2.49	478	2.09
175	5.71	251	3.98	327	3.06	403	2.48	479	2.09

TABLE FOR THE CONVERSION OF RATES INTO GRADIENTS—Continued.

Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Feet.	°	*Feet.*	°	*Feet.*	°	*Feet.*	°	*Feet.*	°
480	2.08	556	1.80	632	1.58	708	1.41	784	1.28
481	2.08	557	1.80	633	1.58	709	1.41	785	1.27
482	2.07	558	1.79	634	1.58	710	1.41	786	1.27
483	2.07	559	1.79	635	1.57	711	1.41	787	1.27
484	2.07	560	1.79	636	1.57	712	1.40	788	1.27
485	2.06	561	1.78	637	1.57	713	1.40	789	1.27
486	2.06	562	1.78	638	1.57	714	1.40	790	1.27
487	2.05	563	1.78	639	1.56	715	1.40	791	1.26
488	2.05	564	1.77	640	1.56	716	1.40	792	1.26
489	2.04	565	1.77	641	1.56	717	1.39	793	1.26
490	2.04	566	1.77	642	1.56	718	1.39	794	1.26
491	2.04	567	1.76	643	1.56	719	1.39	795	1.26
492	2.03	568	1.76	644	1.55	720	1.39	796	1.26
493	2.03	569	1.76	645	1.55	721	1.39	797	1.25
494	2.02	570	1.75	646	1.55	722	1.39	798	1.25
495	2.02	571	1.75	647	1.55	723	1.38	799	1.25
496	2.02	572	1.75	648	1.54	724	1.38	800	1.25
497	2.01	573	1.75	649	1.54	725	1.38	801	1.25
498	2.01	574	1.74	650	1.54	726	1.38	802	1.25
499	2.00	575	1.74	651	1.54	727	1.38	803	1.25
500	2.00	576	1.74	652	1.53	728	1.37	804	1.24
501	2.00	577	1.73	653	1.53	729	1.37	805	1.24
502	1.99	578	1.73	654	1.53	730	1.37	806	1.24
503	1.99	579	1.73	655	1.53	731	1.37	807	1.24
504	1.98	580	1.72	656	1.52	732	1.37	808	1.24
505	1.98	581	1.72	657	1.52	733	1.36	809	1.24
506	1.98	582	1.72	658	1.52	734	1.36	810	1.23
507	1.97	583	1.72	659	1.52	735	1.36	811	1.23
508	1.97	584	1.71	660	1.52	736	1.36	812	1.23
509	1.96	585	1.71	661	1.51	737	1.36	813	1.23
510	1.96	586	1.71	662	1.51	738	1.36	814	1.23
511	1.96	587	1.70	663	1.51	739	1.35	815	1.23
512	1.95	588	1.70	664	1.51	740	1.35	816	1.23
513	1.95	589	1.70	665	1.50	741	1.35	817	1.22
514	1.95	590	1.69	666	1.50	742	1.35	818	1.22
515	1.94	591	1.69	667	1.50	743	1.35	819	1.22
516	1.94	592	1.69	668	1.50	744	1.34	820	1.22
517	1.93	593	1.69	669	1.49	745	1.34	821	1.22
518	1.93	594	1.68	670	1.49	746	1.34	822	1.22
519	1.93	595	1.68	671	1.49	747	1.34	823	1.22
520	1.92	596	1.68	672	1.49	748	1.34	824	1.21
521	1.92	597	1.68	673	1.49	749	1.34	825	1.21
522	1.92	598	1.67	674	1.48	750	1.33	826	1.21
523	1.91	599	1.67	675	1.48	751	1.33	827	1.21
524	1.91	600	1.67	676	1.48	752	1.33	828	1.21
525	1.90	601	1.66	677	1.48	753	1.33	829	1.21
526	1.90	602	1.66	678	1.47	754	1.33	830	1.20
527	1.90	603	1.66	679	1.47	755	1.32	831	1.20
528	1.89	604	1.66	680	1.47	756	1.32	832	1.20
529	1.89	605	1.65	681	1.47	757	1.32	833	1.20
530	1.89	606	1.65	682	1.47	758	1.32	834	1.20
531	1.88	607	1.65	683	1.46	759	1.32	835	1.20
532	1.88	608	1.64	684	1.46	760	1.32	836	1.20
533	1.88	609	1.64	685	1.46	761	1.31	837	1.19
534	1.87	610	1.64	686	1.46	762	1.31	838	1.19
535	1.87	611	1.64	687	1.46	763	1.31	839	1.19
536	1.87	612	1.63	688	1.45	764	1.31	840	1.19
537	1.86	613	1.63	689	1.45	765	1.31	841	1.19
538	1.86	614	1.63	690	1.45	766	1.31	842	1.19
539	1.86	615	1.63	691	1.45	767	1.30	843	1.19
540	1.85	616	1.62	692	1.45	768	1.30	844	1.18
541	1.85	617	1.62	693	1.44	769	1.30	845	1.18
542	1.85	618	1.62	694	1.44	770	1.30	846	1.18
543	1.84	619	1.62	695	1.44	771	1.30	847	1.18
544	1.84	620	1.61	696	1.44	772	1.30	848	1.18
545	1.83	621	1.61	697	1.43	773	1.29	849	1.18
546	1.83	622	1.61	698	1.43	774	1.29	850	1.18
547	1.83	623	1.61	699	1.43	775	1.29	851	1.18
548	1.82	624	1.60	700	1.43	776	1.29	852	1.17
549	1.82	625	1.60	701	1.43	777	1.29	853	1.17
550	1.82	626	1.60	702	1.42	778	1.29	854	1.17
551	1.81	627	1.59	703	1.42	779	1.28	855	1.17
552	1.81	628	1.59	704	1.42	780	1.28	856	1.17
553	1.81	629	1.59	705	1.42	781	1.28	857	1.17
554	1.81	630	1.59	706	1.42	782	1.28	858	1.17
555	1.80	631	1.58	707	1.41	783	1.28	859	1.16

TABLE FOR THE CONVERSION OF RATES INTO GRADIENTS—Continued.

Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Feet.	°	*Feet.*	°	*Feet.*	°	*Feet.*	°	*Feet.*	°
860	1.16	889	1.12	917	1.09	945	1.06	973	1.03
861	1.16	890	1.12	918	1.09	946	1.06	974	1.03
862	1.16	891	1.12	919	1.09	947	1.06	975	1.03
863	1.16	892	1.12	920	1.09	948	1.05	976	1.02
864	1.16	893	1.12	921	1.09	949	1.05	977	1.02
865	1.16	894	1.12	922	1.08	950	1.05	978	1.02
866	1.15	895	1.12	923	1.08	951	1.05	979	1.02
867	1.15	896	1.12	924	1.08	952	1.05	980	1.02
868	1.15	897	1.11	925	1.08	953	1.05	981	1.02
869	1.15	898	1.11	926	1.08	954	1.05	982	1.02
870	1.15	899	1.11	927	1.08	955	1.05	983	1.02
871	1.15	900	1.11	928	1.08	956	1.05	984	1.02
872	1.15	901	1.11	929	1.08	957	1.04	985	1.02
873	1.15	902	1.11	930	1.08	958	1.04	986	1.01
874	1.14	903	1.11	931	1.07	959	1.04	987	1.01
875	1.14	904	1.11	932	1.07	960	1.04	988	1.01
876	1.14	905	1.10	933	1.07	961	1.04	989	1.01
877	1.14	906	1.10	934	1.07	962	1.04	990	1.01
878	1.14	907	1.10	935	1.07	963	1.04	991	1.01
879	1.14	908	1.10	936	1.07	964	1.04	992	1.01
880	1.14	909	1.10	937	1.07	965	1.04	993	1.01
881	1.14	910	1.10	938	1.07	966	1.04	994	1.01
882	1.13	911	1.10	939	1.06	967	1.03	995	1.01
883	1.13	912	1.10	940	1.06	968	1.03	996	1.00
884	1.13	913	1.10	941	1.06	969	1.03	997	1.00
885	1.13	914	1.09	942	1.06	970	1.03	998	1.00
886	1.13	915	1.09	943	1.06	971	1.03	999	1.00
887	1.13	916	1.09	944	1.06	972	1.03	1000	1.00
888	1.13								

SUMMARY OF OBSERVATIONS.

TEMPERATURE.

The mean rate of diminution of temperature with increase of altitude, as determined from 1,217 ascensions and 3,838 observations, taken at elevations of 1,000 feet or more, was 5.0° for each 1,000 feet, or 0.4° less than the true adiabatic rate. The largest gradient, 7.4° per thousand feet, was found up to 1,000 feet, and thereafter there was a steady decrease up to 5,000 feet, the rate of decrease becoming less as the altitude increased. The gradient up to 5,000 feet was 3.8° per thousand feet. Above this altitude there is a tendency toward a slow rise, but the lack of a sufficient number of observations above 6,000 feet forbids a definite statement to that effect. The morning gradients were also greatest up to 1,000 feet, and least up to 5,000 feet, and the rate of decrease was about the same as the mean rate, the curves showing a very close agreement in this respect. (See plates 2 and 4.) The average morning gradient was 4.8° per thousand feet. The afternoon gradients were larger, but not decidedly so, the average value being 5.8° per thousand feet. The greatest rate of decrease is still found at 1,000 feet, and the least up to 5,000 feet, if the few observations at 7,000 feet are not considered as of equal weight. The morning, afternoon, and mean gradients for the different elevations from 1,000 to 8,000 feet, inclusive, are given in the following table:

DECREASE OF TEMPERATURE FOR EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

	1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
	°	°	°	°	°	°	°	°	°	°
Morning	7.2	5.5	4.8	4.0	3.7	3.7	3.9	3.4	3.0	4.8
Afternoon	7.5	6.4	6.0	5.5	4.9	4.3	4.5	3.5	4.9	5.8
Mean	7.4	5.8	5.2	4.4	4.0	3.8	4.1	3.4	4.0	5.0

When the stations of observation were grouped according to their geographical locations it was found that the mean rate of temperature decrease with increase of altitude was much greater in the central Mississippi watershed than in the Upper Lake region, the central West, or the extreme East as represented by the single station at Washington. It was 5.8° per thousand feet, as compared with 4.7° for the central West, 4.6° for the Upper Lake region, and 3.6° for the Atlantic coast. It will be observed also that there is a very close agreement between the means for the Upper Lake region, those for the central West, and the grand mean, and a marked deficiency on the Atlantic coast, where the gradient was 1.4° per thousand feet less than the mean rate. These general statements apply also to the morning results. In the afternoon, however, the differences were quite small, the extreme difference being 0.6° per thousand feet. The maximum gradient, 6.1°, was found in the central Mississippi Basin, and the minimum, 5.4°, in the Upper Lake region. The morning, afternoon, and mean results for the various districts are shown in the following table:

GRADIENT PER THOUSAND FEET.

District.	Morning.	Afternoon.	Mean.
	°	°	°
Atlantic coast	3.4	6.0	3.6
Central Mississippi watershed	5.8	6.1	5.8
Upper Lake region	4.5	5.4	4.6
Central West	4.3	5.6	4.7

RELATIVE HUMIDITY.

The relative humidities at and above the surface of the earth differed but little except at 7,000 feet, where the surface humidity was 11 per cent less than that above. With this exception the greatest difference was 3 per cent, and, except at 2,000 and 8,000 feet, the upper air percentages were the lower. The mean result obtained from all the observations showed 60 per cent at the surface and 58 per cent above, a difference of 2 per cent.

The stations at which there were marked differences were Washington, where the mean difference was 14 per cent; Omaha, where it was 29 per cent; Springfield, Ill., where it was 21 per cent, and Fort Smith, where it was 12 per cent, the surface humidity being the higher except at Fort Smith. At the remaining thirteen stations except Lansing, the upper air humidity equaled or exceeded that at the surface, but the difference at no place exceeded 10 per cent. At nine stations the difference was 5 per cent or less. (See table of mean relative humidity, p. 20.)

VAPOR PRESSURE.

The vapor pressures are expressed in percentages obtained by the formula $\frac{p}{p^\circ}$, in which "p" represents the vapor pressure at any given altitude, and "p°" that observed simultaneously at the earth's surface. The mean of the percentages thus obtained was 59, and there was a steady, though not by any means uniform, decrease with increase of altitude. The percentage at 1,500 feet was 82, and at 8,000 feet, 44. The decrease was most rapid between 2,000 and 5,000 feet, where it averaged 9 per cent for each 1,000 feet. The decrease between 5,000 and 6,000 feet was only 3 per cent, while between 6,000 and 7,000 feet it was 10 per cent. The lowest percentage, 52, was found at Omaha, and the highest, 77, at Pierre. (See table on vapor pressure, p. 20.

A comparative statement of the results obtained from the kite, balloon, and mountain observations is given herewith. In obtaining these results the records of 1,123 kite ascensions were used. There were 4 balloon ascensions by Hammon and 2 by Hazen. It is not known how many were made by Hann, nor how many mountain observations were taken by him.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p^\circ}$ FOR EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

Character of observations.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Kite	0.82	0.78	0.70	0.61	0.52	0.49	0.39	0.44	0.59
Balloon (Hammon)	0.96	0.96	0.87	0.68	0.44	0.59	....	....	0.75
Balloon (Hazen)	0.89	0.83	0.80	0.78	0.67	0.46	0.44	....	0.70
Balloon (Hann)	0.84	0.80	0.66	0.61	0.60	0.54	0.41	0.37	0.60
Mountain (Hann)	0.83	0.81	0.80	0.66	0.61	0.58	0.55	0.47	0.66

Temperature Gradients.

MORNING.

[Bold-faced figures represent degrees per thousand feet; light-faced figures represent number of observations.]

Station.	1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Washington, D. C	**4.6**	**3.9**	**3.6**	**3.2**	**3.0**	**2.8**	**3.1**	**3.0**	**3.0**	**3.4**
	37	41	44	25	17	8	7	3	1	183
Cairo, Ill	**10.5**	**6.4**	**5.7**	**4.3**	**4.4**	**4.1**	....	....	....	**5.9**
	4	19	17	14	12	3	....	....	....	69
Cincinnati, Ohio......	**11.6**	**6.3**	**5.5**	**5.7**	**5.6**	**4.7**	**3.7**	....	....	**6.2**
	1	6	14	13	12	7	2	....	....	55
Fort Smith, Ark......	**7.8**	**6.9**	**6.7**	**5.6**	**3.8**	....	....	....	....	**6.2**
	9	9	9	3	2	....	....	....	....	32
Knoxville, Tenn	**9.1**	**8.2**	**8.2**	**4.5**	**4.5**	....	....	....	....	**6.9**
	1	2	2	4	1	....	....	....	....	10
Memphis, Tenn.......	**8.7**	**6.0**	**4.6**	**3.8**	**3.6**	**3.6**	....	....	....	**5.0**
	7	7	13	19	18	4	....	....	....	68
Springfield, Ill	**6.8**	**5.2**	**4.5**	**4.6**	**3.8**	**3.7**	....	....	....	**4.8**
	7	17	20	11	2	1	....	....	....	58
Cleveland, Ohio	**5.9**	**4.1**	**3.5**	**3.5**	**4.1**	**4.1**	**4.3**	....	....	**4.2**
	22	58	53	48	21	11	1	....	....	214
Duluth, Minn	**4.7**	**4.3**	**3.8**	**4.1**	**4.3**	**4.2**	**4.8**	....	....	**4.3**
	39	47	51	32	20	8	3	....	....	200
Lansing, Mich	**7.8**	**6.0**	**4.8**	**3.9**	**3.8**	**3.8**	....	....	....	**5.0**
	19	19	20	29	20	10	....	....	....	117
Sault Ste. Marie, Mich.	**6.0**	**5.4**	**4.8**	**3.9**	**3.3**	**3.0**	....	....	....	**4.4**
	6	22	28	27	20	13	....	....	....	116
Dodge City, Kans	**6.4**	**5.0**	**4.5**	**3.3**	**2.6**	**2.9**	**3.1**	**3.0**	....	**3.8**
	76	83	79	79	49	19	6	1	....	392
Dubuque, Iowa.......	**7.4**	**5.4**	**4.4**	**3.2**	**3.5**	**3.4**	....	....	....	**4.6**
	9	17	29	24	9	5	....	....	....	93
North Platte, Nebr....	**6.2**	**5.7**	**4.8**	**4.2**	**3.7**	**4.2**	....	....	....	**4.8**
	34	63	52	38	22	7	....	....	....	216
Omaha, Nebr	....	**4.6**	**4.2**	**3.1**	**2.6**	**2.9**	**3.4**	**4.1**	....	**3.6**
	....	19	34	37	26	14	5	2	....	137
Pierre, S. Dak	**5.3**	**4.8**	**4.3**	**3.9**	**3.5**	**4.2**	**4.0**	....	....	**4.3**
	71	83	71	53	34	17	2	....	....	331
Topeka, Kans	**7.0**	**5.4**	**4.1**	**3.3**	**3.3**	**3.8**	**4.5**	....	....	**4.5**
	34	32	43	48	17	9	1	....	....	184
Mean	**7.2**	**5.5**	**4.8**	**4.0**	**3.7**	**3.7**	**3.9**	**3.4**	**3.0**	**4.8**
	376	544	579	504	302	136	27	6	1	2,475

AFTERNOON.

Washington, D. C	**8.1**	**6.5**	**5.8**	**5.5**	**4.9**	**5.1**	....	....	....	**6.0**
	14	11	9	3	2	1	....	....	....	40
Cairo, Ill	**8.0**	**7.0**	**6.5**	**5.8**	**5.2**	**4.7**	....	....	....	**6.2**
	2	14	14	9	7	1	....	....	....	47
Cincinnati, Ohio......	**13.8**	**6.6**	**8.8**	**6.0**	**5.5**	**5.0**	**5.2**	....	....	**7.3**
	2	1	10	6	4	2	1	....	....	26
Fort Smith, Ark	**5.2**	**7.1**	**6.7**	**6.0**	....	....	....	....	....	**6.2**
	3	9	9	5	....	....	....	....	....	26
Knoxville, Tenn	**8.2**	**5.6**	**6.0**	**6.3**	**5.5**	....	....	....	....	**6.3**
	7	6	6	4	1	....	....	....	....	24
Memphis, Tenn	**7.2**	**7.2**	**5.4**	**5.2**	**5.0**	**3.4**	....	....	....	**5.6**
	9	15	14	7	3	1	....	....	....	49
Springfield, Ill	**8.3**	**5.9**	**5.5**	**4.2**	**4.1**	**3.7**	**3.6**	....	....	**5.0**
	8	35	33	17	13	8	2	....	....	116
Cleveland, Ohio	**4.9**	**5.0**	**6.0**	....	....	....	....	....	....	**5.3**
	7	4	2	....	....	....	....	....	....	13
Duluth, Minn..........	**6.0**	**5.9**	**5.8**	**5.1**	**4.2**	**3.3**	**4.2**	....	....	**4.9**
	22	24	32	28	12	5	2	....	....	125
Lansing, Mich	**5.8**	**6.2**	**3.9**	**5.3**	**5.3**	....	....	....	....	**5.3**
	4	4	2	5	2	....	....	....	....	17
Sault Ste. Marie, Mich.	**10.0**	**7.0**	**5.7**	**5.8**	**5.0**	**3.4**	....	....	....	**6.2**
	1	20	18	12	11	2	....	....	....	64
Dodge City, Kans.....	**6.2**	**5.6**	**5.4**	**4.8**	**4.4**	**3.7**	**3.4**	**3.5**	**4.9**	**4.7**
	43	40	39	27	17	9	4	1	1	181
Dubuque, Iowa.......	**6.4**	**6.5**	**4.9**	**4.2**	**2.8**	**2.8**	....	....	....	**4.6**
	10	15	11	11	6	2	....	....	....	55
North Platte, Nebr....	**7.3**	**7.0**	**6.6**	**5.7**	**5.0**	**5.3**	**5.4**	....	....	**6.0**
	36	99	81	64	22	6	1	....	....	309
Omaha, Nebr	....	**7.1**	**6.4**	**6.0**	**5.4**	**5.2**	**5.3**	....	....	**5.9**
	....	10	16	8	8	5	1	....	....	48
Pierre, S. Dak	**7.5**	**6.4**	**6.2**	**6.1**	**5.7**	**6.0**	....	....	....	**6.3**
	25	22	20	12	4	2	....	....	....	85
Topeka, Kans	**7.8**	**6.9**	**6.1**	**5.5**	**4.9**	**4.7**	....	....	....	**6.0**
	34	33	33	24	9	2	....	....	....	135
Mean	**7.5**	**6.4**	**6.0**	**5.5**	**4.9**	**4.3**	**4.5**	**3.5**	**4.9**	**5.8**
	227	362	349	242	121	46	11	1	1	1,360

Temperature Gradient Continued.

MEAN.

Station.	1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Washington, D. C.....	5.6	4.4	4.0	3.5	3.2	3.0	3.1	3.0	3.0	3.6
	51	52	53	28	19	9	7	3	1	223
Cairo, Ill	9.7	6.6	6.0	4.9	4.7	4.3	....	....	....	6.0
	6	33	31	23	19	4	....	....	....	116
Cincinnati, Ohio......	13.0	6.3	6.9	5.8	5.6	4.7	4.2	....	....	6.6
	3	7	24	19	16	9	3	....	....	81
Fort Smith, Ark	7.2	7.0	6.7	5.8	3.8	....	....	....	....	6.2
	12	18	18	8	2	....	....	....	....	58
Knoxville, Tenn	8.4	6.2	6.6	5.4	5.0	....	....	....	....	6.3
	8	8	8	8	2	....	....	....	....	34
Memphis, Tenn	7.8	6.8	5.0	3.8	3.7	3.5	....	....	....	5.1
	16	22	27	26	21	5	....	....	....	117
Springfield, Ill	7.6	5.7	5.1	4.4	4.0	3.7	3.6	....	....	4.9
	15	52	53	28	15	9	2	....	....	174
Cleveland, Ohio	5.7	4.1	3.6	3.5	4.1	4.1	4.3	....	....	4.2
	29	62	55	48	21	11	1	....	....	227
Duluth, Minn.........	5.2	4.8	4.6	4.6	4.3	3.8	4.6	....	....	4.6
	61	71	83	60	32	13	5	....	....	325
Lansing, Mich	7.5	6.0	4.7	4.1	3.9	3.8	....	....	....	5.0
	23	23	22	34	22	10	....	....	....	134
Sault Ste. Marie, Mich.	6.6	6.2	5.2	4.5	3.9	3.0	....	....	....	4.9
	7	42	46	39	31	15	....	....	....	180
Dodge City, Kans.....	6.3	5.2	4.8	3.7	3.1	3.2	3.2	3.2	4 9	4.2
	119	123	118	106	66	28	10	2	1	573
Dubuque, Iowa.......	6.9	5.9	4.6	3.5	3.2	3.3	....	....	....	4.6
	19	32	40	35	15	7	....	....	....	148
North Platte, Nebr....	6.8	6.5	5.9	5.2	4.4	4.7	5.4	....	....	5.6
	70	162	133	102	44	13	1	....	....	525
Omaha, Nebr	....	5.4	4.9	3.6	3.2	3.5	3.8	4.1	....	4.1
	....	29	50	45	34	19	6	2	....	185
Pierre, S. Dak	5.9	5.1	4.8	4.3	3.7	4.4	4.0	....	....	4.6
	96	105	91	65	38	19	2	....	....	416
Topeka, Kans.........	7.4	6.2	4.9	4.0	3.8	3.9	4.5	....	....	5.0
	68	65	76	72	26	11	1	....	....	319
Mean	7.4	5.8	5.2	4.4	4.0	3.8	4.1	3.4	4.0	5.0
	603	906	928	746	423	182	38	7	2	3,835

Temperature Gradients by Geographical Districts.

MORNING.

District.	1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Atlantic coast	4.6	3.9	3.6	3.2	3.0	2.8	3.1	3.0	3.0	3.4
Central Mississippi watershed..........	9.1	6.5	5.9	4.7	4.3	4.0	3.7	....	....	5.8
Upper Lake Region ..	6.1	5.0	4.2	3.8	3.9	3.8	4.6	4.2	....	4.5
Central West.........	6.5	5.2	4.4	3.5	3.2	3.6	3.8	3.6	....	4.3

AFTERNOON.

District.	1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Atlantic coast	8.1	6.5	5.8	5.5	4.9	5.1	....	....	....	6.0
Central Mississippi watershed..........	8.4	6.5	6.5	5.6	5.1	4.2	4.4	....	....	6.1
Upper Lake Region ..	6.7	6.0	5.4	5.4	4.8	3.4	4.2	3.8	....	5.4
Central West.........	7.0	6.6	5.9	5.3	4.7	4.6	3.7	3.5	4.9	5.6

MEAN.

District.	1,000 feet.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Atlantic coast	5.6	4.4	4.0	3.5	3.2	3.0	3.1	3.0	3.0	3.6
Central Mississippi watershed..........	9.0	6.4	6.0	5.0	4.5	4.0	3.9	....	....	5.8
Upper Lake Region ..	6.2	5.3	4.5	4.2	4.1	3.7	4.4	4.0	....	4.6
Central West.........	6.6	5.7	5.0	4.0	3.6	3.8	4.2	3.6	4.9	4.7

MEAN RELATIVE HUMIDITY.

[S = at ground; A = above.]

Station.	1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet.		Mean.	
	S.	A.	S.	A.	S.	A.	S.	A.	S.	A.	S.	A.	S.	A.	S.	A.	S.	A.
Washington, D. C	76	68	75	67	77	64	75	61	80	60	78	66	73	59	79	58	77	63
Cairo, Ill	68	67	65	66	63	64	62	62	60	65	....	....	....	....	....	....	64	65
Cincinnati, Ohio	70	67	65	68	64	63	66	68	65	64	63	70	....	....	....	....	66	67
Fort Smith, Ark	63	72	63	76	63	82	71	79	....	....	....	....	....	....	....	....	65	77
Knoxville, Tenn	55	63	61	71	72	75	64	64	....	....	....	....	....	....	....	....	63	68
Memphis, Tenn	59	70	67	77	72	77	69	69	60	62	....	....	....	....	....	....	65	71
Springfield, Ill	61	45	60	42	57	36	46	24	53	26	50	24	....	....	....	....	54	33
Cleveland, Ohio	74	71	74	72	73	72	69	65	69	75	78	94	....	....	....	....	73	75
Duluth, Minn	70	72	66	69	60	65	62	64	61	57	58	57	54	70	....	....	62	65
Lansing, Mich	78	69	76	68	72	69	61	68	65	64	....	....	....	....	....	....	70	68
Sault Ste. Marie, Mich	80	71	73	69	73	69	63	68	59	73	....	....	....	....	....	....	70	70
Dodge City, Kans	57	52	57	58	55	56	52	42	48	51	45	50	32	42	22	47	46	50
Dubuque, Iowa	70	73	72	73	65	66	66	58	67	71	....	....	....	....	....	....	68	68
North Platte, Nebr	53	56	51	56	47	53	46	52	42	49	30	60	....	....	....	....	45	54
Omaha, Nebr	48	40	50	40	49	33	53	30	62	24	67	15	66	10	....	....	56	27
Pierre, S. Dak	57	63	56	61	55	66	52	60	43	58	48	64	....	....	....	....	52	62
Topeka, Kans	61	69	62	67	63	64	60	59	62	61	63	63	....	....	....	....	62	64
Mean	65	64	64	65	64	63	61	58	60	57	58	56	56	45	50	52	60	58

VAPOR PRESSURE $\left(\frac{p}{p'}\right)$

Station.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.	Mean.
Washington, D. C	0.87	0.82	0.66	0.60	0.54	0.46	0.45	0.34	0.59
Cairo, Ill	.71	.69	.63	.54	.54	....	....	....	.62
Cincinnati, Ohio	.73	.67	.57	.51	.49	.45	....	....	.57
Fort Smith, Ark	.82	.79	.74	.65	....	....	....	....	.75
Knoxville, Tenn	.83	.73	.66	.76	....	....	....	....	.74
Memphis, Tenn	.88	.86	.76	.61	.54	....	....	....	.73
Springfield, Ill	.74	.70	.63	.52	.48	.49	....	....	.59
Cleveland, Ohio	.83	.77	.68	.55	.55	.48	....	....	.64
Duluth, Minn	.82	.79	.74	.64	.57	.56	.45	....	.65
Lansing, Mich	.87	.83	.73	.56	.51	....	....	....	.70
Sault Ste. Marie, Mich	.83	.76	.71	.71	.44	....	....	....	.69
Dodge City, Kans	.85	.84	.80	.71	.61	.56	.51	.55	.68
Dubuque, Iowa	.83	.79	.76	.56	.56	....	....	....	.72
North Platte, Nebr	.78	.72	.66	.57	.40	.65	....	....	.63
Omaha, Nebr	.83	.80	.68	.56	.39	.23	.15	....	.52
Pierre, S. Dak	.90	.86	.75	.72	.69	.69	....	....	.77
Topeka, Kans	.85	.80	.68	.56	.52	.36	....	....	.63
Mean	.82	.78	.70	.61	.52	.49	.39	.44	.59

WASHINGTON, D. C. (ARLINGTON, VA.).

There were in all 87 ascensions and 223 observations, taken during the daytime only, at altitudes of 1,000 feet or over, and the highest altitude attained was 8,211 feet.

The general mean decrease in temperature was 3.6° per thousand feet. The average decrease from the ground up to 1,000 feet of altitude above the kite station was 5.6°; for the other altitudes it was as follows: 1,500 feet, 4.4° per thousand feet; 2,000 feet, 4.0°; 3,000 feet, 3.5°; 4,000 feet, 3.2°; 5,000 feet, 3.0°; 6,000 feet, 3.1°; 7,000 feet, 3.0°; 8,000 feet, 3.0°.

These results are graphically shown on Plate 3. They are the general mean values obtained from observations taken at all hours between 6 a. m. and 7 p. m., Eastern time. No distinction is now made between clear and cloudy days.

It will be noticed that there is a decrease in the gradient up to 4,000 feet, above which altitude the changes were very slight, but nevertheless with a decreasing tendency. The results obtained at altitudes above 4,000 feet are remarkably uniform, considering the paucity of observations and the wide divergence in the weather conditions. But 20 observations were made at altitudes of 5,000 feet or more, and of these 10 were made on clear days, 8 on days on which rain fell, and the remaining 2 on cloudy days without rain.

The negative gradients of temperature or "inversions" during the morning hours of course bear a direct relation to the amount of cloudiness and the velocity of the wind. Thirty-five cases were found with a fairly even distribution through the different months. The inversions, as a rule, extended to an altitude of 1,200 feet, and in over one-half the cases reached 1,500 feet. On May 12, after a clear night with a high relative humidity, there was an inversion of 4.5° up to 2,500 feet, and it did not cease until the kite reached an altitude of 4,100 feet. The most marked case occurred on June 21. The night and early morning up to 6 o'clock had been clear (becoming cloudy, however, by 7 o'clock), and the sun rose at 4.35 a. m. At 5.10 a. m., or thirty-five minutes after sunrise, the temperature at 866 feet elevation was 14° higher than at the ground, and was 10° higher at 5.20 a. m. at an altitude of 1,700 feet. The surface wind was from the west and its velocity 3 miles per hour. A very similar case occurred on June 25, when at 5.40 a. m., one hour and three minutes after sunrise, the temperature at 1,966 feet was 9° higher than at the surface. At this time the surface wind was from the southwest and its velocity also 3 miles per hour.

It is worthy of note that where the inversions were smallest, and incidentally the wind velocities greatest, the wind was always from some northerly point, usually the northwest; and, vice versa, with strong inversions and light winds, the latter were almost always from some southerly point, usually the southwest.

It is interesting also to note the gradients at different times of the day. In the morning the mean rate was 3.4° per thousand feet, the greatest being 4.6° at 1,000 feet, and the least 2.8° at 5,000 feet. The curve in this case fairly approximates that for the mean result, and is given on Plate 1.

In the afternoon, up to a limit of 5,000 feet in altitude, the rate of decrease so nearly approaches the adiabatic rate of 1° for 185 feet, or 5.4° per thousand feet, that the two can be considered as practically one, the mean value obtained being 6.0° per thousand feet, or 0.6° greater than the true adiabatic rate. The lowest rate, 4.9° per thousand feet, was noted at 4,000 feet, and the highest, 8.1° per thousand feet, at 1,000 feet. The corresponding curve for these figures is given on Plate 2.

At all times where clouds were present there was a great decrease in the gradient, resulting in some cases in a complete arrest of the temperature fall, and in others a marked rise, notwithstanding the increased altitude. On July 13, while the kite was in the clouds at altitudes between 2,020 and 2,456 feet, a rise of 5.0° occurred. The extreme range of temperature while the kite was in the clouds was 1.7° for 1,300 feet difference in altitude, or at the rate of 1.3° per thousand feet.

This rise in temperature in the clouds was also noted in several other cases. On June 5, while no rise in temperature occurred, the fall was almost entirely checked, the total decrease for 1,743 feet of ascent having been but 1.1°, or at the rate of 0.6° per thousand feet. An examination of the temperature record for October 8 disclosed some peculiar cloud effects. The flight took place in the morning, the sky being practically obscured by stratus clouds. In this case the rise in temperature began at an altitude of 2,300 feet, about 1,300 feet below the clouds, and continued up to 3,100 feet, after which there was a fall of 2.5° up to 3,600 feet, when the kite entered the clouds, and no change while it remained there. The gradient during the entire flight was very small, occasionally amounting to a complete inversion, particularly at the height of 3,100 feet, when the inversion was as much as 0.6° per thousand feet.

The wind velocity appears to have no effect upon the temperature gradient, inversions not considered, except that during cloudy weather there was usually a marked decrease in the gradient when the surface velocity was about 5 miles per hour or less, and that above correspondingly small as evidenced by the pull on the kite wire.

No deductions regarding the diurnal range of temperature in the upper air were made, owing to the very limited time during which the kite remained at a fixed elevation.

WIND.

The differences in wind direction were indicated by the changes in the azimuths of the kite. These show that in a great majority of cases the general directions above and at the surface are practically the same, the differences being confined to a tendency in the kite to a deflection toward the right. This deflection frequently increased with the altitude, but rarely equaled 90 degrees. In a few instances, not over five or six, the kite was deflected toward the left, but not to any great extent except in one case, on May 27, when the deflection toward the left was about 140 degrees. It should also be stated that in a majority of the cases where the kite was deflected toward the left the velocity of the wind diminished with increase of altitude, as shown by the pull on the kite wire.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity records show that in a great majority of instances, under normal clear conditions, the change with altitude is largely a question of wind direction, or really of the relative positions of the high and low pressure areas. With northerly winds, particularly northwesterly, there was as a rule a marked decrease in the relative humidity with increase of altitude, while with southerly winds the rule was no change or a steady increase, usually the latter, and with easterly winds a decided increase. The drying character of the northwest winds was sometimes noticed at different intervals during the same ascension as the upper currents changed direction from time to time.

In the presence of clouds and rain, or with the latter a few hours before or after the flight, an increase was the rule, but frequently not until after an altitude of 2,500 or 3,000 feet had been reached. But one case was recorded of total saturation while the kite was in the clouds. In one other case, on October 8, the relative humidity fell 22 per cent in fifteen minutes just previous to entering the clouds, remaining at the low point until the kite left the clouds, when it again rose to its former height.

The vapor pressure results for Washington are given below, and are expressed in fractions of the vapor pressure observed simultaneously at the earth's surface $\left(\frac{p}{p^\circ}\right)$ in which "p" represents the vapor pressure at any given altitude and "p°" that at the earth's surface.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p^\circ}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.
0.87	0.82	0.66	0.60	0.54	0.46	0.45	0.34

The computations of the gradients with the general summary of the results are given in the following table.

The first column under each altitude shows the rate of change of altitude for 1° F. change in temperature, while the second column shows the gradient of the temperature for each 1,000 feet of altitude.

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
1898.																				
May 9, a. m			843	1.2	582	1.7														
10, p. m					165	6.1														
12, a. m			350	2.9	192	5.2					272	3.7	539	1.9						
12, a. m													298	3.4	446	2.2	335	3.0		
13, a. m			142	7.0																
14, a. m			350	2.9	192	5.2														
18, p. m	105	9.5	163	6.1																
19, a. m	500	2 0	339	2.9					510	2.0										
24, a. m	467	2.1	1,130	0.9																
30, p. m	869	1.2	244	4.1	230	4.3			223	4.5										
31, a. m					1,140	0.9	569	1.8												
31, a. m							277	3.6												
June 3, p. m	173	5.8	190	5.3	190	5.3	169	5.9												
4, a. m	170	5.9	336	3.0	262	3.8														
8, a. m	120	8.3																		
8, p. m	126	7.9	118	8.5	139	7.2														
9, a. m			83	12.0	111	9.0	180	5.6	218	4.6										
12, a. m	212	4.7																		
14, a. m							754	1.3	553	1.8	492	2.0	339	2.9						
15, a. m							250	4.0												
21, a. m									272	3.7	299	3.3								
22, a. m					400	2.5	271	3.7	214	4.7										
23, a. m					247	4.0	298	3.4	291	3.4	272	3.7								
24, a. m					570	1.8														
25, a. m									340	2.9	312	3.2	297	3.4						
26, a. m									657	1.5	377	2.7								
29, a. m	141	7.1	170	5.9	153	6.5														
July 2, p. m							219	4.6												
8, a. m	122	8.2																		
9, a. m	394	2.5	159	6.3	200	5.0	173	5.8												
10, a. m							398	2.5	348	2.9	354	2.8	290	3.4	282	3.5				
11, a. m					234	4.3														
18, p. m	91	11.0																		
20, p. m	75	13.3																		
21, a. m	834	1.2	629	1.6	633	1.6														
28, p. m	273	3.7	285	3.5	282	3.5														
30, a. m	250	4.0	264	3.8																
Aug. 2, a. m	299	3.3																		
3, a. m	104	9.6	130	7.7																
4, a. m	246	4.1	404	2.5	734	1.4	553	1.8	305	3.3										
5, a. m	1,000	1.0	703	1.4	647	1.5	333	3.0												
7, p. m	141	7.1	166	6.0																
16, p. m	119	8.4	142	7.0	163	6.1														
17, a. m			122	8.2	135	7.4														
17, p. m	84	11.9	98	10.2	152	6.6														
17, p. m																				
18, a. m			146	6.8																
18, p. m	137	7.3																		
22, p. m	111	9.0																		
24, a. m	724	1.4																		
24, p. m	105	9.5	136	7.4	144	6.9	167	6.0	188	5.3	195	5.1								
27, a. m	438	2.3	403	2.5	211	4.7														
29, a. m	88	11.4	418	2.4	135	7.4														
30, a. m	139	7.2																		
Sept. 2, a. m					814	1.2														
26, p. m	123	8.1	180	5.6																
27, a. m			630	1.6	276	3.6	254	3.9												
29, a. m	116	8.6																		
Oct. 9, a. m	236	4.2	310	3.2	260	3.8														
10, p. m			125	8.0	168	6.0														
12, a. m					1,161	0.9	283	3.5												
15, a. m			483	2.1	510	2.1	408	2.5	288	3.5										
17, a. m	749	1.3	290	3.4																
19, a. m	838	1.2			695	1.4														
22, a. m	250	4.0	501	2.0	792	1.3														
23, a. m			646	1.5	277	3.6														
24, a. m			119	8.4	151	6.6														
25, a. m									1,956	0.5										
25, a. m									848	1.2	1,131	0.9								
27, a. m	357	2.8	423	2.4	219	4.6														
31, a. m			2,020	0.5	529	1.9	258	3.9												
CLOUDY.																				
1898.																				
May 6, a. m	617	1.6	924	1.1																
11, a. m					2,370	0.4														
16, a. m							250	4.0					298	3.4	291	3.4				
25, a. m					546	1.4														
26, a. m	254	3.9																		
27, a. m	122	8.2	165	6.1	179	5.6	208	4.8												

Temperature—Cloudy—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
1898.																				
June 5, a. m....	314	3.2	234	4.3	239	4.2	271	3.7												
5, a. m....			164	6.1																
11, a. m....	187	5.3	199	5.0																
16, a. m....			252	4.0	266	3.8	313	3.2	262	3.8										
July 4, a. m....							1,771	0.6	326	3.1										
5, a. m....	380	2.6	251	4.0	249	4.0														
13, a. m....	346	2.9					594	1.7												
13, a. m....			255	3.9	594	1.7	442	2.3												
15, a. m....			496	2.0	358	2.8														
22, a. m....			1,650	0.6	294	3.4														
23, a. m....	310	3.2	225	4.4																
25, a. m....	474	2.1	161	6.2																
Aug. 9, a, m....	114	8.8																		
10, a. m....					461	2.2	600	1.7	529	1.9			801	8.3						
10, a. m....					207	4.8														
14, a. m....							265	3.8												
19, a. m....	147	6.8																		
19, a. m....	175	5.7																		
27, a. m....					93	10.8														
Oct. 2, a. m....	590	1.7																		
6, a. m....					1,371	0.7	221	4.5												
8, a. m....					1,046	1.0			1,064	0.9										
18, a. m....	348	2.9	266	3.8	262	3.8														
SUMMARY.																				
CLEAR.																				
Morning..........		4.8		3.8		3.7		3.4		3.1		2.8		3.0		2.8		3.0		3.4
Afternoon..........		8.1		6.5		5.8		5.5		4.9		5.1								6.0
Mean....		6.0		4.6		4.2		3.7		3.4		3.0		3.0		2.8		3.0		3.7
CLOUDY.																				
Morning..........		4.3		4.0		3.4		3.0		2.4				3.4		3.4				3.4
Afternoon..........																				
Mean....		4.3		4.0		3.4		3.0		2.4				3.4		3.4				3.4
COMBINED.																				
Morning..........		4.6		3.9		3.6		3.2		3.0		2.8		3.1		3.0		3.0		3.4
Afternoon..........		8.1		6.5		5.8		5.5		4.9		5.1								6.0
Mean....		5.6		4.4		4.0		3.5		3.2		3.0		3.1		3.0		3.0		3.6

INVERSIONS.

CLEAR.

Date.	400 feet.		800 feet.		1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.		2,500 feet.		3,000 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 12, a. m....													556	1.8		
14, a. m....			103	9.7	210	4.8										
25, a. m....			471	2.1												
31, a. m....					604	1.7	2,696	0.4								
June 1, a. m....			69	14.5	91	11.0										
1, a. m....			108	9.3												
14, a. m....							284	3.5	583	1.7	2,380	0.4				
15, a. m....	86	11.6			275	3.6	743	1.3								
21, a. m....			62	16.1			101	9.9	170	5.9	392	2.6	1,731	0.6		
22, a. m....	78	12.8	188	5.3			392	2.6	1,228	0.8						
23, a. m....	54	18.5	115	8.7			336	3.0								
24, a. m....			72	13.9			106	9.4	143	7.0	211	4.7	403	2.5		
25, a. m....			69	14.5			104	9.6	146	6.8	218	4.6	982	1.0		
26, a. m....			72	13.9			126	7.9								

Inversions—Clear—Continued.

Date.	400 feet.		800 feet.		1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.		2,500 feet.		3,000 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
July 3, a. m.			130	7.7	158	6.3			220	4.5	259	3.9	767	1.3		
3, a. m.			223	4.5												
4, a. m.			195	5.1			172	5.8	221	4.5	383	2.6	602	1.7		
10, a. m.	85	11.8	192	5.2			260	3.8	539	1.9	1,187	0.8				
11, a. m.	55	18.2	100	10.0	137	7.3	236	4.2								
Aug. 2, a. m.	149	6.7	236	4.2	546	1.8	778	1.3								
Sept. 1, a. m.			88	11.4			147	6.8								
2, a. m.			252	4.0			276	3.6	356	2.8						
27, a. m.	147	6.8	578	1.7												
Oct. 12, a. m.			268	3.7			433	2.3	857	1.2	4,240	0.2				
15, a. m.			838	1.2												
19, a. m.									2,472	0.4						
23, a. m.			234	4.3												
25, a. m.			120	8.3			167	6.0	334	3.0	636	1.6	1,677	0.6		
31, a. m.			111	9.0			509	2.0	1,658	0.6						
CLOUDY.																
May 11, a. m.					404	2.5			1,593	0.6	1,187	0.8				
19, a. m.			819	1.2			601	1.4					1,106	0.9	6,376	0.2
24, 5 p. m.							509	2.0								
July 22, a. m.			546	1.8												
Aug. 14, a. m.			346	2.9			636	1.6	3,272	0.3						
Oct. 6, a. m.			182	5.5			582	1.7	1,460	0.7						
8, a. m.			970	1.0			1,044	1.0	988	1.0					1,570	0.6
21, a. m.			2,970	0.3												

CAIRO, ILL.

TEMPERATURE.

At Cairo there were considered 39 ascensions and 116 observations at altitudes of 1,000 feet or more, and the greatest altitude attained was 5,577 feet.

The mean gradient was 6° for each 1,000 feet. It decreased quite rapidly up to 3,000 feet and very slowly thereafter. The value up to 1,000 feet is particularly large, being 9.7° per thousand feet, while up to 1,500 feet there is a sharp fall to 6.6°.

The morning gradients were steadily and quite uniformly less than the afternoon ones, except up to 1,000 feet, where the morning value reached 10.5° per thousand feet, 2.5° greater than the afternoon one. The averages for all elevations differed but little.

The clear and cloudy weather gradients did not maintain a steady relation toward each other. Up to 2,000 and 5,000 feet the former were the greater, while up to 3,000 feet there was a marked change in the opposite direction. Above 4,000 feet there was very little difference. Cloud effects were as a rule quite marked. There was usually a decided decrease in the rate of temperature fall, and in a number of cases the fall was changed into a rise. After the kite emerged from the clouds the temperature change would be slower than it had been before the clouds were encountered. On July 13 the temperature fall was only 4.5° while the kite was rising from 2,700 to 5,000 feet. From 3,750 to 5,000 feet the fall was but 0.5°. On July 28 there was rise of 3° while the kite rose from 3,150 to 3,450 feet, followed by a further rise of 1° up to 4,000 feet, where the kite emerged from the clouds. Above 4,000 feet a slow fall commenced. On September 4, while a thunderstorm was in progress, there was a rise in the temperature of 2° just as the rain began, followed in a few minutes by a fall of 6° while the kite was rising from 2,100 to 2,800 feet.

Neither wind direction nor velocity appeared to exert any influence upon the temperature gradient.

WINDS.

Wind directions did not vary materially from the usual rule. Neither was the amount of deflection of the kite marked except in one instance, when it varied from 90° to 135° just after the termination of a shower. There were five cases of deflection toward the left, varying in amount from 30° to 90°. In two of these cases a thunderstorm followed shortly.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidities, both above and at the surface, were almost exactly alike, the extreme difference above being but 5 per cent and that at the surface 8 per cent. Except at 5,000 feet the difference between the surface and upper-air humidities did not exceed 1 per cent.

Cloud effects were quite noticeable both while the kite was enveloped in clouds and while rain conditions were present. A rise usually resulted, followed by a fall, as the cloud or rain conditions disappeared. On July 28 there was a fall in the humidity from 90 to 42 per cent as the kite emerged from the clouds.

The vapor-pressure results were very similar to those obtained at Cincinnati and Springfield—stations also located in the great Mississippi Basin.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.
0.71	0.69	0.63	0.54	0.54

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 15, p. m.					216	4.6	198	5.1	205	4.9	215	4.7		
18, a. m.			164	6.1	189	5.3	212	4.7	207	4.8	210	4.8		
27, p. m.			111	9.0	152	6.5	196	5.1	227	4.4				
29, p. m.			129	7.8	170	5.9								
30, a. m.			121	8.3	113	8.8								
June 5, p. m.			157	6.4	137	7.3								
13, p. m.			218	4.6										
19, p. m.			125	8.0	133	7.5	155	6.5						
24, p. m.			114	8.8	143	7.0	163	6.1	157	6.4				
July 9, a. m.			158	6.3	253	3.8	274	3.6	276	3.7	272	3.7		
10, a. m.			151	6.6	202	5.0	341	2.9	236	4.2				
11, a. m.							669	1.6	240	4.2				
12, a. m.			133	7.5	148	6.8	158	6.3						
19, a. m.	118	8.5	161	6.2										
Aug. 7, p. m.	167	6.0												
Sept. 3, p. m.			178	5.6	200	5.0								
5, a. m.			188	5.3	186	5.4	333	3.0	242	4.1				
7, p. m.	100	10.0												
10, a. m.	71	14.1												
11, a. m.			97	10.3	108	9.3								
Oct. 16, p. m.			214	4.7	170	5.9	177	5.6	179	5.6				
23, p. m.			131	7.6	174	5.7	283	3.5						
24, a. m.			121	8.3	149	6.7	273	3.7	267	3.7				
30, p. m.			125	8.0	152	6.6								

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 19, a. m.	74	13.5	109	9.2	133	7.5	143	7.0	165	6.1				
20, a. m.	167	6.0	175	5.7	163	6.1	183	5.5	200	5.0				
June 11, p. m.					139	7.2	152	6.6	187	5.3				
17, p. m.			130	7.7	143	7.0	163	6.1						
25, a. m.			170	5.9	241	4.1								
25, p. m.			118	8.5	125	8.0	145	6.9	178	5.6				
26, a. m.			350	2.9	278	3.6	242	4.1	267	3.7				
July 4, a. m.			194	5.2										
8, a. m.			177	5.6	154	6.5								
13, a. m.			876	1.1	563	1.8	372	2.7	310	3.2	258	3.9		
20, a. m.			141	7.1	182	5.5	186	5.4	222	4.5				
28, a. m.			177	5.6	230	4.3	232	4.3						
28, p. m.									250	4.0				
Sept. 4, p. m.			135	7.4	157	6.4								
21, p. m.			255	3.9										
22, a. m.			126	7.9	159	6.3	167	6.0	178	5.6				

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	....	11.3	....	5.6	....	6.4	....	3.7	....	4.1	....	4.2	....	5.9
Afternoon	....	8.0	....	6.9	....	6.2	....	5.3	....	5.3	....	4.7	....	6.1
Mean	....	9.6	....	6.0	....	6.3	....	4.4	....	4.6	....	4.4	....	5.9
CLOUDY.														
Morning	....	9.8	....	7.2	....	5.1	....	4.9	....	4.7	....	3.9	....	5.9
Afternoon	....	....	....	7.0	....	7.2	....	6.9	....	5.0	....	....	....	6.5
Mean	....	9.8	....	7.1	....	5.7	....	5.5	....	4.8	....	3.9	....	6.5
COMBINED.														
Morning	....	10.5	....	6.4	....	5.7	....	4.3	....	4.4	....	4.1	....	5.9
Afternoon	....	8.0	....	7.0	....	6.5	....	5.8	....	5.2	....	4.7	....	6.2
Mean	....	9.7	....	6.6	....	6.0	....	4.9	....	4.7	....	4.3	....	6.0

CINCINNATI, OHIO.

TEMPERATURE.

At Cincinnati there were 38 ascensions and 81 observations at altitudes of 1,000 feet or more, and the greatest altitude reached was 6,313 feet.

The mean decrease in temperature with increase of altitude was 6.6° for each 1,000 feet, the highest gradient found at any station. The abnormally large gradient of 13° per thousand feet occurs up to 1,000 feet, but as there were but three observations at this altitude it is very probable that a greater number would have resulted in a reduced gradient. Up to 1,500 feet the gradient is less than one-half as large.

The rate of temperature diminution decreased, as usual, with increase of altitude, except up to 2,000 feet, but it is perhaps true that the increase at this elevation is more apparent than real, as the gradient up to 1,500 feet is comparatively small and is the mean of but seven observations. At 1,500 and from 3,000 up to 5,000 feet the morning and afternoon gradients were nearly equal, but up to 1,000, 2,000, and 6,000 feet there is considerable variation, the afternoon ones being the greater.

While the mean clear and mean cloudy weather gradients were exactly equal, they varied greatly and irregularly at the different elevations. At some elevations the clear ones were the greater and at others the cloudy ones. The remarkable gradient of 14.7° per thousand feet was noted in the early afternoon of June 8, during cloudy weather.

In the few instances in which the kite was in proximity to the clouds there did not appear to have been any variations in the temperatures that could not be accounted for by difference of elevation.

WINDS.

Wind directions adhered to the usual rule of deflection toward the right, but not to any decided degree, the maximum deflection having been about 90°, and that in one or two cases only. There were four cases of deflection in the opposite direction of from 20° to 40°, and three of them were followed by rain in one or two hours.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity results above agreed very closely with those at the surface, the greatest difference, 7 per cent, being found at 6,000 feet. With this exception the greatest difference was 3 per cent.

The approach of clouds or rain had the usual effect of producing a rise in the humidity, which was more marked in the case of rain. Vapor-pressure results follow below. There is an excellent agreement with the values obtained at Springfield, Ill., a neighboring station.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p^0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.
0.73	0.67	0.57	0.51	0.49	0.45

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 8, a. m									457	2.2	526	1.9	342	2.9		
15, p. m							202	5.0								
29, p. m					168	6.0										
June 3, p. m			106	9.4												
4, a. m									364	2.7	217	4.6				
4, p. m					99	10 0										
4, p. m					82	12.2										
15, a. m					177	5.6										
19, a. m			94	10.6												
19, p. m	77	13.0			83	12.0	120	8.3								
24, a. m							104	9.6								
July 3, a. m					148	6.8										
9, a. m			500	2.0												
9, p. m					154	6.5	340	2.9								
10, a. m					135	7.4	139	7.2								
19, a. m			109	9.2												
19, p. m					96	10.4										
28, p. m			256	3.9	173	5.8										
29, a. m							165	6.1	170	5.9	199	5.0				
Aug. 3, a. m					164	6.1	176	5.7	211	4.7						
3, a. m									173	5.8	208	4.8				
12, a. m					174	5.7										
29, a. m	86	11.6														
Sept. 6, a. m							353	2.8	338	3.0						
6, a. m			131	7.6	155	6.5	158	6.3	170	5.9						
7, a. m							171	5.8	173	5.8						
11, a. m					1,046	1.0										
12, a. m							230	4.3								
14, p. m					117	8.5										
18, a. m					171	5.8	177	5.6	216	4.6	242	4.1				
24, p. m					100	10.0	149	6.7								
27, p. m					125	8.0										
CLOUDY.																
May 10, a. m									67	14.9						
10, p. m											189	5.3	193	5.2		
11, a. m							158	6.3								
11, p. m									138	7.2						
28, a. m											267	6.7	222	4.5		
28, p. m											216	4.6				
June 8, p. m	68	14.7														
11, p. m									244	4.1						
July 18, a. m					186	5.4										
20, a. m					131	7.6	154	6.5	176	6.0	179	5.6				
25, p. m					148	6.8	174	5.7								
Aug. 3, p. m									206	4.9						
24, a. m							171	5.8	178	5.6						
Sept. 4, a. m			819	1.1	657	1.5	469	2.1								
5, a. m					962	1.0										
26, a. m					122	8.2										
Oct. 1, p. m							136	7.4	170	5.9						

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	......	11.6	......	7.4	......	5.9	......	5.9	......	4.5	......	4.1	......	2.9	......	6.0
Afternoon	......	13.0	......	6.6	......	9.0	......	5.7	......	......	......	......	......	......	......	8.6
Mean	......	12.8	......	7.1	......	7.5	......	5.9	......	4.5	......	4.1	......	2.9	......	6.3
CLOUDY.																
Morning	......	......	......	1.1	......	4.7	......	5.2	......	8.8	......	6.2	......	4.5	......	5.1
Afternoon	......	14.7	......	......	......	6.8	......	6.6	......	5.5	......	5.0	......	5.2	......	7.3
Mean	......	14.7	......	1.1	......	5.1	......	5.6	......	6.9	......	5.6	......	4.8	......	6.3
COMBINED.																
Morning	......	11.6	......	6.3	......	5.5	......	5.7	......	5.6	......	4.7	......	3.7	......	6.2
Afternoon	......	13.8	......	6.6	......	8.8	......	6.0	......	5.5	......	5.0	......	5.2	......	7.3
Mean	......	13.0	......	6.3	......	6.9	......	5.8	......	5.6	......	4.7	......	4.2	......	6.6

FORT SMITH, ARK.

TEMPERATURE.

Owing to the absence of sufficient wind to fly the kite, there were only 19 ascensions and 58 observations made at Fort Smith at altitudes of 1,000 feet or more. Of these 6 ascensions and 19 observations were made during June; 4 ascensions and 16 observations during July; 2 ascensions and 4 observations during August, and 7 ascensions and 19 observations during September. The highest altitude attained was 5,431 feet.

The average hourly wind velocity at the surface was 5.6 miles from May to October, inclusive, with a maximum average of 6.3 miles in May and a minimum of 4.5 miles in August.

The mean decrease in temperature with increase of altitude was 6.1° for each 1,000 feet. The gradient decreased slowly up to 2,000 feet, and quite rapidly thereafter, a departure from the conditions generally prevailing elsewhere.

The observations were equally divided between the mornings and afternoons, and the means were exactly equal. The gradients also differed but little up to the different altitudes, except at 1,000 feet, where the morning one was 2.6° larger.

The clear and cloudy weather gradients were exactly alike up to 2,000 feet; up to 1,500 feet the cloudy one was 1.2° larger than the clear one, while up to the remaining altitudes the clear weather ones were the greater.

There were but two instances in which the kite was enveloped in clouds, and both were apparently without effect upon the temperature. Wind directions and velocities were without influence upon the gradients. It is of interest to note, however, in connection with the winds, that there were no ascensions made with northerly winds, and that the greater portion were made with southwesterly winds, except in September, when they were mostly southeasterly.

WINDS.

The wind directions conformed to the usual rule, although the deflections were slight, except in one instance when it amounted to 90°. But one case of deflection toward the left was noticed. It was quite well marked, gradually increasing with increase of altitude from 25° to 60°, and was followed within an hour by light showers of very brief duration.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidities were considerably greater above than at the surface, the greatest difference—19 per cent—occurring at 3,000 feet and the least—8 per cent—at 4,000 feet. The mean difference was 12 per cent.

Cloud effects were, as usual, confined to an increase in the humidity as the kite entered the clouds, followed by a corresponding fall as the kite emerged.

Vapor pressure results as follows were determined. They do not correspond very well with any others found in the West except those at Omaha:

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.
0.82	0.79	0.74	0.65

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 26, a. m	129	7.8	142	7.0	154	6.5						
26, p. m							144	6.9				
July 19, a. m	104	9.6			143	7.0	147	6.8				
19, p. m			192	5.2	190	5.3	145	6.9				
28, p. m			146	6.8	141	7.1	159	6.3				
Aug. 5, a. m	128	7.8										
Sept. 3, p. m			144	6.9	108	9.3	194	5.2				
4, a. m			263	3.8	189	5.3						
5, a. m			248	4.0	205	4.9	192	5.2				
5, p. m			158	6.3								
15, a. m			91	11.0	115	8.7						
15, p. m							221	4.5				
16, a. m	142	7.0	160	6.2	159	6.3						
CLOUDY.												
June 11, a. m			119	8.4	113	8.8						
16, p. m			122	8.2								
20, a. m	120	8.3										
24, p. m	101	9.9	102	9.7	119	8.4						
24, p. m			132	7.6	129	7.8						
25, a. m	128	7.8	136	7.4	161	6.2	211	4.7	274	3.6		
25, a. m									244	4.1		
July 18, a. m	127	7.9	141	7.1	154	6.5						
18, p. m					146	6.8						
30, p. m	492	2.0	179	5.6	246	4.1						
Aug. 31, p. m	278	3.6	147	6.8	184	5.4						
Sept. 17, a. m	145	6.9										
29, a. m	133	7.5	136	7.4								
29, p. m					166	6.0						

SUMMARY.

CLEAR.

Morning		8.0		6.4		6.4		6.0				6.7
Afternoon				6.3		7.2		6.0				6.5
Mean		8.0		6.4		6.7		6.0				6.8

CLOUDY.

Morning		7.7		7.6		7.2		4.7		3.8		6.2
Afternoon		5.2		7.6		6.4						6.4
Mean		6.7		7.6		6.7		4.7		3.8		5.9

COMBINED.

Morning		7.8		6.9		6.7		5.6		3.8		6.2
Afternoon		5.2		7.1		6.7		6.0				6.2
Mean		7.2		7.0		6.7		5.8		3.8		6.2

KNOXVILLE, TENN.

TEMPERATURE.

At Knoxville there were only 19 ascensions and 34 observations at altitudes of 1,000 feet or more, and the highest altitude attained was 4,482 feet. On May 5, before the regular observations were commenced, an altitude of 6,058 feet was reached.

The mean decrease in temperature with increase of altitude was 6.3° for each 1,000 feet. Owing, most likely, to the great scarcity of observations, the rate of change of the temperature varied irregularly as the elevation increased, instead of decreasing steadily. Except up to 4,000 feet, the morning gradients were greater than the afternoon ones, particularly at 1,500 and 2,000 feet. The average morning result was 0.6° greater than the afternoon one.

As there were but three observations made during cloudy weather, the results given above are practically clear-weather results.

There were but two ascensions in which the kite came into contact with clouds. In one the clouds appeared to be without effect, while in the other a slight retardation in the rate of temperature fall was noticed.

Neither wind direction nor velocity appeared to have any bearing upon the results.

WINDS.

Wind directions conformed to the usual rule with but one or two exceptions. On one day there was a divergence of the kite toward the left of about 20°, and a thunderstorm occurred several hours later.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity was higher above than at the surface, except at 4,000 feet. The greatest difference was 10 per cent at 2,000 feet.

The vapor pressure results follow: Up to 3,000 feet they agree very well with others from the Ohio Valley northward, and are not greatly dissimilar to those found at Washington. At 4,000 feet, where there were but two observations, the results appear to be abnormally high.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_o}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.
0.83	0.73	0.66	0.76

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 10, p. m			134	7.5	101	9.9	98	10.0				
11, p. m	158	6.3										
12, a. m			146	6.8								
16, a. m							337	3.0				
25, p. m	176	5.7										
26, p. m			266	8.8								
30, a. m			103	9.7	101	9.9						
June 3, p. m			263	3.8	241	4.1						
3, p. m	400	2.5	375	2.7	267	3.7						
4, p. m	91	11.0										
21, p. m					161	6.2						
25, a. m	110	9.1										
July 10, p. m							152	6.6				
11, a. m					153	6.5	153	6.5				
11, p. m	100	10.0	114	8.8	140	7.1						
12, a. m							242	4.1				
12, p. m			150	6.7	187	5.3						
Aug. 3, p. m	101	9.9										
Sept. 23, a. m							221	4.5	222	4.5		
CLOUDY.												
June 17, p. m	81	12.3										
24, p. m							238	4.2	183	5.5		
July 13, p. m							235	4.3				

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	....	9.1	....	8.2	....	8.2	....	4.5	....	4.5	....	6.9
Afternoon	....	7.6	....	5.6	....	6.0	....	8.3	....	....	....	6.9
Mean	....	7.8	....	6.2	....	6.6	....	5.8	....	4.5	....	6.2

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	....	....	....	....	....	....	....	....	....	....	....	....
Afternoon	....	12.3	....	....	....	....	....	4.2	....	5.5	....	7.3
Mean	....	12.3	....	....	....	....	....	4.2	....	5.5	....	7.3

COMBINED.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	....	9.1	....	8.2	....	8.2	....	4.5	....	4.5	....	6.9
Afternoon	....	8.2	....	5.6	....	6.0	....	6.3	....	5.5	....	6.3
Mean	....	8.4	....	6.2	....	6.6	....	5.4	....	5.0	....	6.3

MEMPHIS, TENN.

TEMPERATURE.

At Memphis there were 37 ascensions and 117 observations at altitudes of 1,000 feet or more, and the greatest height reached was 5,243 feet.

The mean decrease in temperature with increase of altitude was 5.1° per thousand feet, and there was a steady decrease in the rate up to the highest altitude. The decrease was quite rapid up to 3,000 feet and very slow thereafter.

The morning gradients were considerably less than the afternoon ones except up to 1,000 and 5,000 feet. Up to the former elevation there is a difference of 1.5° per thousand feet, the morning gradient reaching the high value of 8.7° per thousand feet. Up to 5,000 feet the difference in favor of the morning gradient was trifling.

By way of exception to the usual rule, the cloudy weather gradients were greater than the clear weather ones up as far as 1,500 feet, the difference being 1.4° per thousand feet up to the latter elevation. Up to the higher elevations the usual rule holds, but the differences were comparatively small.

Cloud effects, while not at all decided, were quite frequent and constant. There was usually a suspension of the temperature change as the kite came into contact with the clouds, followed by a slower rise or fall than had obtained before the clouds were encountered.

Wind velocities were without effect. The directions, however, appeared to have some bearing upon the gradients. It was noticed that with winds from the northwest to east the temperature decreased more rapidly than with those from any other direction. The greatest gradients were found with north to east winds and the least with south to west ones.

WINDS.

The usual rule of deflection toward the right obtained except in one or two insignificant instances.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidities above 1,500 feet did not differ greatly, the extreme range being 15 per cent. They were greatest at 2,000 and 3,000 feet, and least at 5,000 feet. At 3,000 feet they were greater than the surface humidities, while at 4,000 and 5,000 feet the two were almost exactly alike.

Clouds and the near approach of rain caused a rise in the humidity, which in the former case was followed by a fall as soon as the kite was removed from cloud influence.

The vapor pressure results are given below. At the lower elevations they agree quite well with others in the Upper Mississippi Valley. The nearest approach to the Memphis values was found at Lansing, Mich.

Diminution of Vapor Pressure with Altitude.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.
0.88	0.86	0.76	0.61	0.54

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 24, p. m	213	4.7	191	5.2	390	2.6								
24, p. m					248	4.0	196	5.1						
24, p. m			730	1.4	571	1.8								
26, a. m	101	9.9	131	7.6	119	8.4								
26, p. m			111	9.0										
July 10, a. m							760	1.3	267	8.7	227	4.4		
10, p. m			151	6.6	158	6.3	190	5.3						
11, a. m									312	3.2	311	3.2		
11, p. m	1,009	1.0	750	1.3	499	2.0	307	3.3						
12, p. m	173	5.8												
29, a. m							427	2.3	221	4.5				
30, a. m					1,000	1.0	284	3.5	244	4.1				
Sept. 4, a. m			172	5.8	215	4.7	201	3.8						
5, a. m							246	4.1	246	4.1				
5, p. m									174	5.7				
5, p. m					133	7.5	168	6.0	182	5.5				
6, a. m	116	8.6												
8, a. m	77	13.0												
14, a. m			200	5.0										
14, p. m			153	6.5	166	6.0								
14, p. m			141	7.1										
Oct. 3, a. m					192	5.2	219	4.6	222	4.5				
3, p. m			102	9.8	136	7.4								
11, p. m			136	7.4	141	7.1	162	6.2						
16, a. m					350	2.9	321	3.1	285	3.1				
16, p. m	101	9.9	123	8.1	133	7.5	170	5.9						
18, a. m							300	3.8	222	4.5				
22, a. m	163	6.1	103	9.7	222	4.5								
24, a. m							375	2.7	513	1.9				
24, p. m	107	9.3	130	7.7	145	6.9	207	4.8	259	3.9	293	3.4		
26, a. m			194	5.2	173	5.8	250	4.0						
26, p. m	117	8.5												
CLOUDY.														
June 25, a. m							419	2.4	335	5.0				
27, a. m							545	1.8	398	2.5	314	3.2		
27, a. m					136	7.4	139	7.2	225	4.4				
July 8, a. m					250	4.0	294	3.4						
9, a. m							283	3.5	308	3.2				
9, a. m							273	3.7						
13, a. m					367	2.7								
17, a. m					554	1.8								
19, a. m			319	3.1										
19, p. m					304	3.3								
20, a. m							509	2.0	244	4.1				
20, a. m									225	4.4				
22, a. m	178	5.6												
25, a. m	174	5.7												
Aug. 26, p. m	271	3.7												
30, a. m			177	5.6	201	5.0								
30, p. m	100	10.0	84	11.9										
31, a. m	83	12.0												
Sept. 7, p. m			91	11.0	132	7.6								
9, p. m	85	11.8	128	7.8										
10, a. m					151	6.6								
12, a. m									992	1.0				
12, a. m							294	3.4	334	3.0				
12, p. m			128	7.8	158	6.3								
22, a. m							375	2.7	364	2.7	294	3.4		

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		2,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	....	9.4	....	6.6	....	4.6	....	3.3	....	3.7	....	3.8	....	5.2
Afternoon	....	6.5	....	6.4	....	5.4	....	5.2	....	5.0	....	3.4	....	5.3
Mean	....	7.7	....	6.5	....	5.1	....	4.1	....	4.1	....	3.7	....	5.2
CLOUDY.														
Morning	....	7.8	....	4.4	....	4.6	....	3.3	....	3.4	....	3.3	....	4.5
Afternoon	....	8.5	....	9.6	....	5.7	....	....	....	....	....	....	....	7.9
Mean	....	8.1	....	7.9	....	5.0	....	3.3	....	3.4	....	3.3	....	5.2
COMBINED.														
Morning	....	8.7	....	6.0	....	4.6	....	3.3	....	3.6	....	3.6	....	5.0
Afternoon	....	7.2	....	7.2	....	5.4	....	5.2	....	5.0	....	3.4	....	5.6
Mean	....	7.8	....	6.8	....	5.0	....	3.8	....	3.7	....	3.5	....	5.1

SPRINGFIELD, ILL.

TEMPERATURE.

Of the Springfield series of observations 174 were considered, having been made during 46 ascensions at altitudes of from 1,000 to 6,000 feet.

The mean rate of decrease of temperature with increase of altitude was found to be 4.9° for each 1,000 feet, the lowest gradient in the Mississippi Valley basin. The greatest gradient, 7.6° for each thousand feet, was found at an elevation of 1,000 feet, and there is a steady decrease up to the highest limits reached. The morning and afternoon curves differ but slightly above 2,000 feet; from the ground up to 2,000 feet the difference varied from 0.7° to 1.5°, being greatest up to 1,500 feet. If all altitudes are considered together, the morning, afternoon, and mean results are almost exactly alike.

The clear and cloudy weather gradients were also quite similar, with values of 5.1° and 4.6° per thousand feet, respectively. The only marked difference was found up to 1,000 feet, where it was 2.4° per thousand feet.

The principal effect of clouds upon the temperature was a diminution of the rate of fall, at times amounting to a complete suspension. On October 29 there was a rise of 5° from 2,100 to 3,700 feet while the kite was in the clouds, and, in consequence, a considerable decrease in the gradient. The opposite effect was noticed on July 18, when there was a fall of 4° while the kite was in the clouds, followed by a rise of 2.5° when it emerged. In some instances the clouds appeared to have no effect.

Wind effects were confined to a decrease in the gradient with increase of velocity, although the two were not at all proportional.

WINDS.

The wind directions conformed to the rule of general agreement which has uniformly obtained. There was the same deflection of the kite toward the right in the upper air; it increased with increase of altitude, but rarely amounted to 90 degrees or more. In one case there was a deflection of 90 degrees toward the left during the ascension, caused by the shifting of the surface wind, the direction of the upper remaining the same, and a severe thunderstorm took place about eight hours after the change occurred.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity was decidedly less above than at the surface, but there was comparatively little change above 1,500 or 2,000 feet, except when clouds were present or when rain had fallen a few hours before or after. When there were clouds there would be a marked rise, amounting at times to total saturation, as long as the kite was in the clouds, a fall taking place as soon as it emerged.

When rain had fallen shortly before or after the ascension the humidity would be high, usually higher than at the surface, and would remain so for hours, although the surface humidity was falling rapidly. In clear weather the upper air humidity was usually less than that at the surface, sometimes approaching zero, while during cloudy or rainy weather the upper would be the higher, but not with so great differences as obtained under reverse conditions.

The vapor pressure percentages follow below:

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.
0.74	0.70	0.63	0.52	0.48	0.49

TEMPERATURE

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 10, a. m.	......	......	348	2.9	231	4.3	234	4.3	......	......	......	......	......	......	......	......
19, a. m.	......	......	......	......	229	4.4	......	......	......	......	......	......	......	......	......	......
19, a. m.	......	......	......	......	140	7.1	......	......	......	......	......	......	......	......	......	......
21, a. m.	110	9.1	......	......	......	......	......	......	......	......	......	......	......	......	......	......
24, a. m.	......	......	316	3.2	198	5.1	......	......	......	......	......	......	......	......	......	......
24, p. m.	......	......	204	4.9	......	......	......	......	......	......	......	......	......	......	......	......
29, a. m.	......	......	......	......	606	1.7	266	3.8	......	......	......	......	......	......	......	......
29, p. m.	......	......	158	6.3	141	7.1	......	......	......	......	......	......	......	......	......	......
July 1, p. m.	85	11.0	119	8.4	115	8.7	......	......	......	......	......	......	......	......	......	......
2, a. m.	......	......	175	5.7	182	5.5	187	5.3	......	......	......	......	......	......	......	......
9, a. m.	......	......	......	......	806	1.2	......	......	......	......	......	......	......	......	......	......
10, a. m.	104	9.6	131	7.6	122	8.2	......	......	......	......	......	......	......	......	......	......
13, p. m.	95	10.5	208	4.8	182	5.5	......	......	......	......	......	......	......	......	......	......
14, p. m.	81	12.3	143	7.0	......	......	......	......	......	......	......	......	......	......	......	......
20, a. m.	......	......	153	6.5	......	......	......	......	......	......	......	......	......	......	......	......
27, p. m.	......	......	109	9.2	......	......	......	......	......	......	......	......	......	......	......	......
Aug. 15, p. m.	......	......	......	......	257	3.9	342	2.9	302	3.3	300	3.3	......	......	......	......
21, a. m.	......	......	148	6.8	176	5.7	196	5.1	......	......	......	......	......	......	......	......
21, p. m.	......	......	134	7.5	174	5.7	......	......	225	5.4	213	4.7	......	......	......	......
23, p. m.	162	6.2	150	6.7	177	5.6	241	4.1	......	......	......	......	......	......	......	......
23, p. m.	......	......	430	2.3	314	3.2	......	......	......	......	......	......	......	......	......	......
26, p. m.	......	......	204	4.9	246	4.1	......	......	......	......	......	......	......	......	......	......
27, p. m.	119	8.4	110	9.1	157	6.4	......	......	......	......	......	......	......	......	......	......
29, a. m.	161	6.2	463	2.2	352	2.8	250	4.0	......	......	......	......	......	......	......	......
30, p. m.	253	4.0	193	5.2	162	6.2	......	......	......	......	......	......	......	......	......	......
Sept. 29, p. m.	......	......	152	6.6	176	5.7	202	5.0	188	5.3	207	4.8	......	......	......	......
29, p. m.	......	......	......	......	......	......	......	......	182	5.5	......	......	......	......	......	......
Oct. 2, p. m.	......	......	195	5.2	174	5.7	187	5.3	......	......	......	......	......	......	......	......
23, p. m.	......	......	......	......	......	......	610	1.6	457	2.2	538	1.9	......	......	......	......
26, p. m.	......	......	......	......	136	7.4	181	5.5	176	5.7	214	4.7	......	......	......	......
27, p. m.	......	......	156	6.4	142	7.0	......	......	......	......	......	......	......	......	......	......
27, p. m.	......	......	......	......	......	......	264	3.8	331	3.0	......	......	......	......	......	......
27, p. m.	......	......	247	4.0	224	4.5	370	2.7	......	......	......	......	......	......	......	......
28, p. m.	......	......	140	7.1	......	......	......	......	......	......	......	......	......	......	......	......
28, p. m.	......	......	136	7.4	175	5.7	259	3.9	232	4.3	238	4.2	270	3.7	......	......
28, p. m.	......	......	......	......	......	......	......	......	......	......	302	3.3	......	......	......	......
31, p. m.	......	......	150	6.7	276	3.6	......	......	......	......	......	......	......	......	......	......
31, p. m.	......	......	741	1.3	702	1.4	......	......	......	......	......	......	......	......	......	......

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 12, a. m.	......	......	132	7.6	154	6.5	154	6.5	......	......	......	......	......	......	......	......
15, a. m.	265	3.8	635	1.6	434	2.3	......	......	......	......	......	......	......	......	......	......
25, a. m.	316	3.2	252	4.0	254	3.9	......	......	250	4.0	......	......	......	......	......	......
27, a. m.	124	8.1	......	......	181	5.5	210	4.8	......	......	......	......	......	......	......	......
27, p. m.	105	9.5	......	......	123	8.1	181	5.5	......	......	......	......	......	......	......	......
July 17, p. m.	......	......	105	9.5	110	9.1	......	......	......	......	......	......	......	......	......	......
17, p. m.	......	......	274	3.6	......	......	......	......	......	......	......	......	......	......	......	......
18, a. m.	......	......	131	7.6	165	6.1	163	6.1	......	......	......	......	......	......	......	......
18, p. m.	......	......	......	......	127	7.9	132	7.6	......	......	......	......	......	......	......	......
28, a. m.	......	......	330	3.0	494	2.0	......	......	......	......	......	......	......	......	......	......

Temperature—Cloudy—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Aug. 2, a. m....	128	7.8	128	7.8												
8, p. m....			95	10.5	115	8.7	163	6.1								
11, p. m....	215	4.7	213	4.7	203	4.9	311	3.2								
16, p. m....			152	6.6	196	5.1	205	4.9	241	4.1						
20, p. m....			200	5.0	267	3.7										
Sept. 17, a. m....			202	5.0	188	5.3	228	4.4								
17, p. m....			168	6.0	183	5.5										
17, p. m....			302	3.3	276	3.6										
24, a. m....			153	6.5	265	3.8	294	3.4	274	3.6	270	3.7				
24, p. m....							832	1.2	357	2.8	369	2.7	289	3.5		
30, p. m....			229	4.4	209	4.8										
30, p. m....			255	3.9	250	4.0										
Oct. 5, p. m....			150	6.7	200	5.0										
5, p. m....			212	4.7												
17, p. m....			268	3.7	313	3.2	368	2.7	287	3.5						
29, a. m....			216	4.6	226	4.4	315	3.2								
29, p. m....									419	2.4						
29, p. m....			180	5.6	182	5.5	200	5.0	193	5.2						
30, a. m....			188	5.3	235	4.3										
30, p. m....			127	7.9	165	6.1										

SUMMARY.

CLEAR.

	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
Morning........		8.3		5.0		4.6		4.5								5.6
Afternoon......		8.7		6.0		5.4		3.9		4.3		3.8		3.7		5.1
Mean........		8.6		5.8		5.1		4.1		4.3		3.8		3.7		5.1

CLOUDY.

	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
Morning........		5.7		5.3		4.4		4.7		3.8		3.7				4.6
Afternoon......		7.1		5.7		5.7		4.5		3.6		2.7		3.5		4.7
Mean........		6.2		5.6		5.2		4.6		3.7		3.2		3.5		4.6

COMBINED.

	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
Morning........		6.8		5.2		4.5		4.6		3.8		3.7				4.8
Afternoon......		8.3		5.9		5.5		4.2		4.1		3.7		3.6		5.0
Mean........		7.6		5.7		5.1		4.4		4.0		3.7		3.6		4.9

CLEVELAND, OHIO.

TEMPERATURE.

There were 93 ascensions and 227 observations at Cleveland at altitudes of 1,000 feet or over, and the highest altitude reached was 6,135 feet. The mean decrease in temperature with increase of altitude was 4.2° for each 1,000 feet, the smallest gradient in the lake region. Beginning with the highest gradient, that up to 1,000 feet, there is a quite rapid decrease up to 2,000 feet, the minimum being reached up to 3,000 feet, after which there is an increase, which becomes very slow above 4,000 feet.

But 13 observations were made in the afternoon, so that the mean results are practically those of the morning alone. The few that were made in the afternoon gave results varying from 4.9° per thousand feet up to 1,000 feet to 6° up to 2,000 feet.

The clear and cloudy weather gradients differed only slightly, but, in marked contrast to previous experiences, it was found that the cloudy-weather ones were the greater at all altitudes, with an extreme difference of 0.6° per thousand feet up to 5,000 feet.

The cloud effects were not markedly different from those at other stations. The most frequent result was a suspension of the temperature fall as the kite ascended. Once or twice there was a slight rise in the temperature, and on two occasions there was a considerable fall. On June 8 there was a fall of 4° while the kite remained in the clouds in the neighborhood of 5,000 feet elevation from 8 a. m. to 12 m. On July 28 there was a fall of 7.5° between the 3,500 and 4,400 foot levels while the kite was in the midst of the stratus clouds, and an almost similar fall, 8.5°, at the surface. The gradient, consequently, remained practically unchanged.

Twenty-one cases of inversion of temperature were found, five of them extending to the height of 2,000 feet. None were particularly marked except those of October 10 and 17. On the former date there was an inversion of 8° at the height of 1,455 feet, and on the latter date one of 10° at the height of 1,500 feet. The inversions were more marked with ESE. to SSE. winds, those from the warmest quarter, than with those from any other direction.

WINDS.

As the kite ascended its deflections were in accordance with the usual rule, with but five minor exceptions. The deflections were not marked, rarely amounting to as much as 90°, and there was a tendency toward an increase as the altitude became greater. In five cases there was a deflection in the opposite direction, amounting in one instance to 45°, and in two of them thunderstorm conditions were present.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative-humidity results were much the same above and at the surface, only the single observation at 6,000 feet showing any marked difference. The greatest difference, with the single exception noted, was at 5,000 feet, where the humidity was 6 per cent greater than at the surface. The approach of rain was frequently indicated by a sharp rise in the humidity as the altitude increased, but only a very few hours before the rain began. The presence of clouds almost invariably resulted in a rise in the humidity of from 5 to 10 per cent, followed by a nearly corresponding fall as the kite emerged. In a few cases the clouds were without apparent effect.

The vapor-pressure results follow below.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.
0.83	0.77	0.68	0.55	0.55	0.48

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Grad.-ent.	Rate.	Gradient.
June 5, p. m....	154	6.5	219	4.6	......	......	......	......	......	......	......	......	......	......	......	......
6, p. m....	376	2.7	......	......	......	......	......	......	......	......	......	......	......	......	......	......
7, a. m....	......	......	782	1.3	......	......	......	......	......	......	......	......	......	......	......	......
8, a. m....	......	......	......	......	......	......	......	......	......	......	356	2.8	......	......	......	......
8, a. m....	......	......	......	......	......	......	......	......	......	......	172	5.8	......	......	......	......
9, p. m....	235	4.3	......	......	......	......	......	......	......	......	......	......	......	......	......	......
11, a. m....	......	......	......	......	......	......	590	1.7	......	......	......	......	......	......	......	......
11, a. m....	......	......	......	......	......	......	373	2.7	......	......	......	......	......	......	......	......
12, a. m....	......	......	216	4.6	......	......	275	3.6	......	......	252	4.0	......	......	......	......
14, a. m....	......	......	......	......	228	4.4	236	4.2	240	4.2	......	......	......	......	......	......
15, a. m....	......	......	135	7.4	169	5.9	239	4.2	269	3.7	......	......	......	......	......	......
20, a. m....	......	......	443	2.3	183	5.5	353	2.8	......	......	......	......	......	......	......	......
21, a. m....	......	......	141	7.1	154	6.5	175	5.7	......	......	......	......	......	......	......	......
22, p. m....	166	6.0	201	5.0	166	6.0	......	......	......	......	......	......	......	......	......	......
23, a. m....	739	1.4	203	4.9	......	......	......	......	......	......	......	......	......	......	......	......
24, a. m....	169	5.9	494	2.0	393	2.5	357	2.8	......	......	......	......	......	......	......	......
26, a. m....	......	......	270	8.7	341	2.9	286	3.5	254	3.9	237	4.2	......	......	......	......
27, a. m....	......	......	474	2.1	569	1.8	421	2.4	......	......	......	......	......	......	......	......
28, a. m....	......	......	182	5.5	188	5.3	215	4.7	203	4.9	......	......	......	......	......	......
28, a. m....	......	......	......	......	......	......	150	6.7	......	......	......	......	......	......	......	......
28, p. m....	......	......	......	......	165	6.1	......	......	......	......	......	......	......	......	......	......
30, a. m....	111	9.0	630	1.6	425	2.4	313	3.2	......	......	......	......	......	......	......	......

Temperature—Clear—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
July 1, a. m.			218	4.6	246	4.1										
2, a. m.			306	3.3	387	2.6	262	3.8								
2, a. m.	144	6.9	143	7.0												
3, a. m.			222	4.5	262	3.8	224	4.5	208	4.8						
5, a. m.	135	7.4	152	6.6												
6, p. m.	168	6.0														
8, a. m.			171	5.8	172	5.8										
9, a. m.	106	9.4														
10, a. m.	139	7.2			161	6.2	147	6.8								
11, a. m.			198	5.1	236	4.2										
12, p. m.			182	5.5												
13, p. m.	204	4.9	198	5.1												
19, a. m.			258	3.9	258	4.0	186	5.4								
20, a. m.			279	3.6	289	3.5	268	3.7	241	4.1	238	4.2				
21, a. m.			155	6.5	290	3.4										
22, a. m.	154	6.5	286	3.5												
23, a. m.			310	3.2	199	5.2										
25, a. m.			310	3.2	285	3.5	226	4.4								
28, a. m.					409	2.4	212	4.7	211	4.7						
29, a. m.			1,550	0.6	506	2.0										
31, a. m.	200	5.0	178	5.6												
Aug. 3, a. m.			431	2.3	403	2.5	327	3.1	256	3.9						
5, a. m.	98	10.2														
7, a. m.			620	1.6	466	2.1	247	4.0								
12, a. m.	162	6.2	362	2.8	203	4.9										
15, a. m.							432	2.3	280	3.6	312	3.2				
19, a. m.	161	6.2	124	8.1												
22, a. m.	316	3.2														
23, a. m.							529	3.9	287	3.5						
26, a. m.			156	6.4	160	6.2	211	4.7								
27, a. m.			143	7.0	170	5.9										
28, a. m.					447	2.2										
29, a. m.							405	2.5								
31, a. m.					352	2.8										
Sept. 1, a. m.			142	7.0												
2, a. m.			774	1.3	528	1.9										
3, a. m.	464	2.2	334	3.0												
8, a. m.			258	3.9	238	4.2	182	5.5								
11, a. m.	119	5.0														
13, a. m.							619	1.6	294	3.4						
14, a. m.	267	3.7	327	3.1	305	3.3										
16, a. m.			209	4.8	197	5.1										
18, a. m.			288	3.5	284	3.5	257	3.9	234	4.3	222	4.5	231	4.3		
19, a. m.					799	1.3	606	1.7	460	2.2	316	3.2				
25, a. m.			1,012	1.0												
29, a. m.	184	5.4														
Oct. 3, a. m.					842	1.2	302	3.3								
6, a. m.			768	1.3	280	3.6										
10, a. m.							204	4.9								
12, a. m.			264	3.8	277	3.6										
16, a. m.	290	3.4														
19, a. m.					1,480	0.7	464	2.2	240	4.2						
20, a. m.							600	1.7								
CLOUDY.																
June 10, a. m.			1,021	1.0			280	3.6								
19, a. m.	242	4.1					257	3.9	182	5.5						
25, p. m.	244	4.1														
July 4, a. m.	133	7.5														
18, a. m.			180	5.6	225	4.4										
19, a. m.									174	5.7	185	5.4				
Aug. 3, a. m.											219	4.6				
4, a. m.			149	6.7	178	5.6										
16, a. m.							1,455	0.7	279	3.6						
17, a. m.			205	4.9	337	3.0	250	4.0								
24, a. m.							477	2.1	353	2.8	271	3.7				
25, a. m.			844	1.2	804	1.2	311	3.2								
26, a. m.									193	5.2						
29, a. m.									288	3.5						
Sept. 5, a. m.			234	4.3	248	4.0	407	2.5								
6, a. m.	119	8.4	130	7.7												
7, a. m.			185	5.4	208	4.8	208	4.8								
10, a. m.			183	5.5	187	5.3	206	4.9								
15, a. m.			291	3.4	334	3.0	216	4.6								
23, a. m.			270	3.7	286	3.5	286	3.5	267	3.7						
26, a. m.	194	5.2														
Oct. 1, a. m.			501	2.0												
5, a. m.					255	3.9										
13, a. m.			776	1.2	689	1.5										
14, a. m.			226	4.4	229	4.4	231	4.3								
15, a. m.			235	4.3	241	4.1	242	4.1								
23, a. m.			245	4.1	250	4.0	279	3.6								

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		5.8		4.1		3.4		3.4		4.0		4.0		4.3		4.1
Afternoon		5.1		5.0		6.0										5.4
Mean		5.6		4.1		3.5		3.4		4.0		4.0		4.3		4.1

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		6.3		4.1		3.8		3.6		4.3		4.6				4.4
Afternoon		4.1														4.1
Mean		5.9		4.1		3.8		3.6		4.3		4.6				4.4

COMBINED.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		5.9		4.1		3.5		3.5		4.1		4.1		4.3		4.2
Afternoon		4.9		5.0		6.0										5.3
Mean		5.7		4.1		3.6		3.5		4.1		4.1		4.3		4.2

INVERSIONS.

Date.	1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 10	352	2.8			1,605	0.6		
11					1,530	0.7		
Aug. 13	961	1.0						
16					539	1.9	983	1.0
24					3,186	0.3		
31					1,456	0.7		
Sept. 1	526	1.9						
9	204	4.9						
13					411	2.4	585	1.7
21			255	3.9	332	3.0		
25	1,065	0.9						
28	462	2.2						
30			265	3.8				
30			276	3.6	408	2.5		
Oct. 1	234	4.3						
1	237	4.2						
2					1,528	0.7		
3					2,910	0.3		
10					182	5.5	493	2.0
17			136	7.4	150	6.7	800	1.2
19					629	1.6		
20					602	1.7	1,979	0.5

DULUTH, MINN.

TEMPERATURE.

At Duluth 96 ascensions and 328 observations were investigated, and the highest altitude attained was 6,832 feet.

The mean decrease in temperature with increase of altitude was 4.5° per thousand feet. The largest gradient, 5.2° per thousand feet, occurred up to 1,000 feet, and thereafter there was a slow and regular decrease to 3.8° up to 5,000 feet, and a more rapid increase to 4.6° up to 6,000 feet.

The morning average was slightly less, and the afternoon one slightly greater than the mean, but in neither was the rate of change regular up to the different altitudes.

The gradients in clear and cloudy weather only differed 0.1° per thousand feet, and the greatest difference in any altitude was 0.6° up to 3,000 feet.

An exceptionally large gradient was found on October 29, when, in cloudy weather, at 1 o'clock in the afternoon, the gradient was 14.9° at 1,000 feet elevation. Brisk NNW. winds were blowing from a high area to the northwestward, but no marked fall in temperature had occurred in that region, nor did any occur at Duluth.

While the cloud effects were more uniform than at most other stations, they were not so decided except in the one important instance described below. The usual result was a suspension of the temperature fall as the kite rose; at times a rise of 2° or 3°, and a decrease in the rate of fall as the kite rose above the clouds. On June 17 the temperature rose 3° as the kite reached the clouds; then fell 5° while in the clouds, and afterwards rose 1° in reaching an altitude of 4,650 feet, 1,000 feet above the top of the clouds.

A very remarkable inversion, due to clouds, occurred during the afternoon of June 10. There were cumulus clouds at an altitude of 1,391 feet, and the temperature rose steadily from 43° at the surface to 54° at the clouds, resulting in an inversion of 11°, or at the rate of 7.9° per thousand feet. The temperature remained at the highest point for about ten minutes, the elevation continuing practically the same. As the kite left the clouds in descent, the temperature fell almost instantly from 54° to 39°, the altitude being 1,038 feet.

Twenty-seven cases of temperature inversion were found, and many of them are worthy of note, not for the extent of the inversion, but for the time of day at which they occurred. Nearly one-half the cases occurred between the late morning and the middle of the afternoon, and during cloudy weather. It appears that they are almost entirely due to the effect of the easterly winds, mostly northeasterly, from Lake Superior, the warming effect of these winds being sensible at times to the height of nearly 6,000 feet. Thus, on May 26, at 1.30 p. m., there was an inversion of 3° at 5,100 feet elevation, or at the rate of 0.6° per thousand feet; on June 3, one of 2° at 5,372 feet elevation, or at the rate of 0.4° per thousand feet, and on September 20, at 4 p. m., one of 1° at 5,714 feet elevation, or at the rate of 0.2° per thousand feet. In all these cases the upper wind directions were almost diametrically opposite to those at the surface. On August 31 there was an inversion of 10° up to 4,000 feet elevation, or at the rate of 2.5° per thousand feet, and again the directions of the upper and lower currents differed 180°. On September 29 there was an inversion of 13° at 2,900 feet altitude, or at the rate of 4.5° per thousand feet; but in this case the upper winds were from the ESE. and SSE. The inversion of 15° on June 10, due to clouds, has already been noticed.

WINDS.

As a rule the wind directions differed less than usual as the kite ascended, the deflection of the latter, of course, being toward the right in a great majority of cases. The few wide divergences were toward the left, and were due to the abnormal northeast wind from the lake. At such times there would usually be an inversion of temperature, and frequently a thunderstorm a few hours later.

This northeast wind was very often purely local, being due to lake influence, and corresponding in a minor way to the sea breezes at the ocean shore. They were sometimes not more than 700 or 800 feet in depth, and rarely more than 2,000 feet. Some peculiar temperature effects, due to this east wind, were noted on July 19. The winds, both above and at the surface, were from south to southwest during the greater portion of the day, but in the afternoon an east wind set in from the lake, the upper direction remaining unchanged. This east wind was about 2,000 feet in depth, as indicated by the thermograph trace sheet, the temperature beginning to fall as soon as the kite came down into it from above, falling from 77° to 70°. The wind from the east continued until about 7 p. m., when it again changed to westerly, and the temperature rose from 67° to 80°.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidities decreased steadily, though slowly, with increase of altitude; the highest, 72 per cent, being found at 1,500 feet, and the lowest, 57 per cent, at 6,000 feet. There was very little difference between the upper air and the surface humidities, the maximum, 5 per cent, occurring at 3,000 feet, and the minimum, 1 per cent, at 6,000 feet. The surface humidities were less than those above up to 4,000 feet and greater at the higher altitudes.

Owing to the geographical situation of Duluth, at the western end of Lake Superior, the highest humidities occurred with easterly winds and the lowest with those from west to northwest.

The cloud effects upon the humidity were normal, consisting of a rise, more or less decided, but none particularly so, and a return to the preexisting conditions when the kite was freed from cloud influence. The vapor pressure results, as given below, will be found to agree almost exactly with those at Dubuque.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.
0.82	0.79	0.74	0.64	0.57	0.45

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 15, p. m			318	3.1	159	6.3										
16, a. m	96	10.4														
23, a. m			91	11.0			840	1.2								
30, a. m	385	2.6														
30, p. m					129	7.8	216	4.6								
June 8, a. m	99	10.1			174	5.7										
8, p. m			113	8.8	166	6.0										
14, a. m	177	5.6	153	6.5	153	6.5	171	5.8	216	4.6	241	4.1	207	4.8		
19, a. m			536	1.9	295	3.4										
19, a. m					199	5.0										
21, a. m					942	1.1										
21, p. m					517	1.9										
28, p. m	459	2.2			309	3.2	234	4.3	282	3.5						
July 6, a. m			213	4.7	196	5.1	236	4.2	299	3.3						
6, p. m					255	3.9										
8, a. m	242	4.1	280	3.6	298	3.4	244	4.1	426	2.3						
8, p. m					94	10.7										
11, p. m			151	6.6	148	6.8	152	6.6								
12, a. m			647	1.5	380	2.6	212	4.7								
13, p. m	381	2.6	393	2.5	263	3.8	243	4.1								
14, a. m			280	3.6	228	4.4										
17, p. m	246	4.1	215	4.7	212	4.7	256	3.9	244	4.1	406	2.5				
18, a. m			201	5.0	296	3.4										
19, p. m			294	3.4	269	3.7										
20, a. m	111	9.0	106	9.4												
21, a. m			653	1.5	506	2.0										
21, a. m					166	6.0										
21, p. m			168	6.0					292	3.4	554	1.8				
22, p. m			112	8.9	177	5.6	157	6.4								
24, p. m			112	8.9	154	6.5	170	5.9	168	6.0						
25, a. m	371	2.7														
27, a. m			185	5.4	565	1.8	322	3.1	208	4.8						
29, a. m	242	4.1														
29, p. m	85	11.8	110	9.1												
Aug. 4, a. m	564	1.8														
7, a. m	552	1.8	495	2.0	558	1.8	415	2.4	259	3.9	285	3.5				
7, p. m							152	6.6								
8, a. m			241	4.1	227	4.4	188	5.3	199	5.0						
9, a. m			774	1.3	421	2.4	201	5.0								
11, a. m	108	9.3	134	7.5	144	6.9	166	6.0								
11, p. m					125	8.0	133	7.5	177	5.6						
12, a. m	333	3.0	218	4.6	142	7.0										
15, a. m							347	2.9	293	3.4	242	4.1				
16, p. m							144	6.9	159	6.3						
19, a. m			242	4.1	232	4.3	233	4.3	204	4.9						
19, p. m							162	6.2								
20, a. m			126	7.9	156	6.4										
24, p. m	173	5.8	416	2.4	480	2.1	331	3.0								
26, p. m	186	5.4														
Sept. 2, p. m	141	7.1	142	7.0	149	6.7	176	5.7	418	2.4						
3, p. m							163	6.1								
4, a. m	179	5.6	207	4.8	220	4.5	147	6.8								
4, p. m					145	6.9	169	5.9								
5, a. m					447	2.2	219	4.6								
11. a. m					315	3.2										
11, p. m							161	6.2								
16, a. m							419	2.4	255	3.9	263	3.8				
17, a. m			774	1.3	678	1.5	264	3.8	232	4.3	205	4.9				

Temperature—Clear—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Sept. 17. p. m													209	4.8		
18, a. m					509	2.0	228	4.4								
18, p. m							155	6.5								
19, a. m					533	1.9										
19, a. m					317	3.2	293	3.4								
20, p. m							876	1.1								
21, a. m	1,164	0.9														
25, a. m					553	1.8	185	5.4								
27, p. m	167	6.0	147	6.8	193	5.2	182	5.0	344	2.9						
28, a. m	144	6.8	171	5.8	187	5.3										
28. p. m							521	1.9								
30, a. m	426	2.3	578	1.7	648	1.5	267	3.7								
30, p. m									238	4.2	240	4.2				
Oct. 3, a. m	170	5.9	179	5.6	171	5.8	318	3.1	371	2.7						
3, p. m											233	4.3				
6, a. m	157	6.4	202	5.0	281	3.6	254	3.9	237	4.2						
6. p. m											269	3.7	273	3.7		
7, p. m			87	11.5	96	10.4	131	7.6	153	6.5						
8, a. m					433	2.3	133	7.5	142	7.0						
10, p. m	175	5.7	180	5.6	194	5.2	229	4.4								
11, p. m	123	8.1	151	6.6	188	5.3	216	4.6	276	3.6						
14, p. m	135	7.4														
22, a. m	1,019	1.0	292	3.4	224	4.5										
25, a. m			268	3.7	256	3.9	204	4.9	196	5.1						
26, a. m	337	3.0	251	4.0	243	4.1										
31, p. m	119	8.4	157	6.4	164	6.1	277	3.6								
							CLOUDY.									
May 19. p. m			202	5.0	206	4.9										
23, p. m					167	6.0	210	4.8								
24, a. m			317	3.2	242	4.1	348	2.9								
24, p. m							348	2.9	334	3.0						
27, a. m			340	2.9	333	3.0										
June 1, a. m					332	3.0	301	3.3	313	3.2	267	3.7	242	4.1		
1, a. m									137	7.3	171	5.8	185	5.4		
1. p m					159	6.3	158	6.3								
2, a. m			1,420	0.7												
4, p. m	390	2.6	676	1.5												
9, a. m			201	5.0	205	4.9										
9, p. m	204	4.9														
10, p. m	346	2.9														
17, a. m			306	3.3	321	3.1	486	2.1	267	3.7						
17, p. m					216	4.6	188	5.3								
21, a. m	292	3.4														
23, a. m	1,064	0.9	427	2.3	322	3.1										
24, a. m	181	5.5	205	4.9												
24, a. m	629	1.6														
July 7, a. m	343	2.9	467	2.1												
23, a. m	629	1.6														
28, a. m			129	7.8	148	6.8										
30, a. m	890	1.1														
Aug. 5, a. m			163	1.6												
16, a. m	168	6.0	200	5.0	214	4.7	156	6.4								
25, p. m	145	6.9			126	7.9										
28, a. m	252	4.0	264	3.8	296	3.4	493	2.0	352	2.8	297	3.4				
31, a. m	157	6.4														
Sept. 3, a. m	140	7.1	128	7.8	152	6.6										
6, a. m	249	4.0	536	1.9	485	2.1										
6, a. m					207	4.8	201	5.0	236	4.2						
7, p. m	164	6.1	172	5.8	183	5.5	177	5.6								
9, a. m	297	3.4	222	4.5	198	5.1										
15, p. m	320	3.1	172	5.8	188	5.3										
Oct. 1, a. m	94	10.6														
2, p. m	219	4.6	199	5.0	208	4.8	208	4.8	201	5.0						
4, a. m	243	4.1														
5, a. m	107	9.3	155	6.5												
9, a. m	170	5.9	177	5.6												
9, p. m					312	3.2										
15, a. m	353	2.8	265	3.8	258	3.9	760	1.3								
21, p. m	156	6.4	194	5.2												
24, p. m	196	5.1	176	5.7	201	5.0										
29, a. m			90	11.1												
29, p. m	67	14.9														
30, a. m	142	7.0	159	6.3	182	5.5	204	4.9								

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	......	4.8	......	4.1	......	3.6	......	4.3	......	4.3	......	4.1	......	4.8	......	4.3
Afternoon	......	6.2	......	6.4	......	6.0	......	5.2	......	4.3	......	3.3	......	4.2	......	5.1
Mean	......	5.3	......	5.0	......	4.5	......	4.8	......	4.3	......	3.7	......	4.4	......	4.6

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	......	4.6	......	4.5	......	4.2	......	3.5	......	4.2	......	4.3	......	4.8	......	4.3
Afternoon	......	5.8	......	4.9	......	5.3	......	5.0	......	4.0	......	......	......	......	......	5.0
Mean	......	5.0	......	4.6	......	4.7	......	4.1	......	4.2	......	4.3	......	4.8	......	4.5

COMBINED.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	......	4.7	......	4.3	......	3.8	......	4.1	......	4.3	......	4.2	......	4.8	......	4.3
Afternoon	......	6.0	......	5.9	......	5.8	......	5.1	......	4.2	......	3.3	......	4.2	......	4.9
Mean	......	5.2	......	4.8	......	4.6	......	4.6	......	4.3	......	3.8	......	4.6	......	4.5

INVERSIONS.

Date.	800 feet.		1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.		2,500 feet.		3,000 feet.		3,500 feet.		4,000 feet.		4,500 feet.		5,000 feet.		5,700 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 17, a. m			252	4.0																				
25, p. m	770	1.3	524	1.9	568	1.8																		
25, p. m			141	7.1																				
26, p. m											219	4.0					392	2.6	773	1.3	1,702	0.6		
June 2, a. m									1,991	0.5														
3, a. m									345	2.9	482	2.1	549	1.8										
3, p. m																	1,911	0.5			2,686	0.4		
10, p. m					126	7.9																		
12, p. m			540	1.9	581	1.7																		
15, p. m					275	3.6																		
19, a. m			260	3.8	641	1.6																		
21, a. m									1,012	1.0														
21, p. m													3,274	0.3										
July 16, a. m	551	1.8																						
Aug. 15, a. m					551	1.8	796	1.3																
30, p. m					2,280	0.4	405	2.5	332	3.0														
31, p. m													257	3.9			404	2.5						
Sept. 5, a. m					2,328	0.4																		
11, a. m			238	4.2			708	1.4																
16, a. m					419	2.4	1,335	0.7																
17, a. m					1,214	0.8																		
18. a. m			204	4.9	654	1.5																		
19, a. m					462	2.2																		
20, a. m			178	5.6	256	3.9			477	2.1	1,386	0.7												
20, p. m																							5,714	0.2
24, a. m					258	3.9	458	2.2	1,151	0.9														
25, a. m					476	2.1																		
26, a. m					316	3.2	1,607	0.6																
29, a. m							1,529	0.7	1,262	0.8														
29, p. m					201	5.0			207	4.8	269	3.7	219	4.6										
Oct. 8, a. m					474	2.1																		
15, a. m															912	1.1	790	1.3						

LANSING, MICH.

TEMPERATURE.

At Lansing 58 ascensions and 131 observations at altitudes above 1,000 feet were considered, and the greatest altitude attained was 5,415 feet. Observations were first taken on June 7. Previous to this date, however, almost daily ascensions were made without the meteorograph and observations of wind direction taken. During the ascension of May 1 an altitude of 7,068 feet was attained.

The mean gradient was 5° per thousand feet, the highest gradient of the lake region stations. There was a steady decrease with increase of altitude; it is quite rapid up to 3,000 feet and slow thereafter. As there were but 17 observations made in the afternoon, the morning results differ but slightly from the means. The few afternoon observations gave gradients varying from 3.9 per thousand feet up to 2,000 feet to 6.2 up to 1,500 feet.

The clear and cloudy weather gradients did not differ greatly except up to 3,000 feet, where there was a difference of 1.5° per thousand feet, the clear-weather gradient—4.5°—being the greater. The clear-weather gradients were uniformly the greater, except up to 4,000 feet. When clouds enveloped or were near the kite the usual temperature rises where noticed, except on one day—August 25—when there was a fall of 3.7° while the kite was descending in dense cumuli from about 2,100 feet altitude to 1,900 feet. On September 26 there was a rise of 8° while the kite was rising in cumulus clouds from 2,700 to 3,200 feet, resulting in a complete inversion of the gradient. There was also an inversion of 1° at an elevation of 2,300 feet on October 12, while the kite was in dense cumuli just previous to the commencement of rain. The direction of the wind appeared to exercise some effect upon the gradients. The greatest were found with the warm winds from the southwest, and the least with the colder ones from the northwest. There were nine days on which inversions of temperature occurred, and on four of them the results were quite marked. On September 29 there was an inversion of 10° at the height of 1,623 feet at 7.38 a. m., steadily decreasing after 7.50 a. m., but was still at 1.5° at 9.54 a m. at an altitude of 1,052 feet. The winds were from the south at the surface and from the southwest above. On October 1 the inversion amounted to 7° at the height of 3,200 feet at 7.50 a. m. and to 5° at 3,500 feet with winds from the east at the surface and from the east-southeast above. On October 29, with east-southeast winds at the surface and southwest to south above, there was an inversion of 13.3° at 8.18 a. m. at the height of 1,082 feet, and at 10.02 a. m. there was still an inversion of 1°.

WINDS.

Wind directions conformed to the usual rule of deflection toward the right in the upper air, but not at all to a marked degree. There were about one dozen exceptions to the rule, but none were decided, neither were they preceded, attended, nor followed by any characteristic phenomena.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity results did not differ greatly. Up to 3,000 feet they were lower than at the surface; the greatest deficiency, 9 per cent, being found at 1,500 feet, and the least, 3 per cent, at 3,000 feet. At 4,000 feet the humidity was 7 per cent greater than at the surface, while at 5,000 feet there was a difference of but 1 per cent. Clouds as a rule caused a slight rise in the humidity, but in at least two instances there was a marked fall while the kite was enveloped in clouds.

The vapor-pressure results follow below. It will be noticed that there is a very satisfactory agreement with the figures for the lake stations at Cleveland, Sault Ste. Marie, and Duluth, at least below the 4,000-foot level.

Diminution of Vapor Pressure with Altitude.

VALUE OF $\frac{p}{p^{\circ}}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.
0.87	0.83	0.73	0.56	0.51

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 8, p. m			127	7.9										
0, a. m											233	4.3		
9, a. m											281	3.6		
14, p. m							172	5.8						
15, a. m							190	5.3						
15, a. m							158	6.3						
18, a. m	103	9.7	131	7.6			214	4.7	210	4.8				
19, a. m	150	6.7					143	7.0	167	6.0	214	4.7		
21, a. m	128	7.8			148	6.8								
23, a. m	81	12.3	200	5.0										
24, a. m							428	2.3	211	4.7	212	4.7		
24, p. m							142	7.0						
25, a. m											717	1.4		
26, a. m							155	6.5						
26, a. m							162	6.2						
28, a. m			189	5.3										
28, a. m	62	16.1	131	7.6	162	6.2								
30, a. m			126	7.9			209	4.8	314	3.2				
July 1, a. m			149	6.7	146	6.8	166	6.0						
1, p m	148	6.8												
2, a. m	96	10.4	133	7.5	614	1.6	276	3.6	257	3.9				
3, a. m									218	4.1				
4, a. m	139	7.2	121	8.3	161	6.2								
4, a. m	94	10.6												
9, a. m							206	4.9	205	4.9				
10, a. m	121	8.3			176	5.7								
18, a. m			147	6.8	191	5.2	181	5.5						
20, a. m			177	5.6	159	6.3	200	5.0	212	4.7				
29, a. m	119	8.4												
Aug. 7, p. m	204	4.9	151	6.6										
11, a. m							180	5.6						
21, p. m			127	7.9										
25, a. m	137	7.3	450	2.2	187	5.3								
28, a m							174	5.7						
31, a m							417	2.4						
Sept. 2, a. m									217	4.6				
3, a. m									233	4.3	220	4.5		
4, a. m									280	3.6	234	4.3		
7, a. m							372	2.7						
8, a. m							698	1.4						
18, a. m	326	3.1			926	1.1	1,166	0.9	318	3.1				
19, a. m									357	2.8	290	3.4		
26, a. m									616	1.6				
28, a. m					174	5.7								
30, a. m	611	1.6							727	1.4	306	3.3		
Oct. 10, a. m			194	5.2	273	3.7	353	2.8						
15, a. m	159	6.3												
28, a. m	357	2.8			333	3.0	316	3.2						
28, p. m			337	3.0	400	2.5	434	2.3						
29, a. m			336	3.0										
29, p. m	174	5.7			189	5.3	208	4.8	239	4.2				

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 12, a. m			229	4.4					270	3.7	277	3.6		
12, a. m									203	4.1				
13, a. m	95	10.5	131	7.6										
20, p. m							148	6.8	157	6.4				
29, a. m					258	3.9	431	2.3	280	3.6				
July 19, a. m			394	2.5										
25, p. m	171	5.8	136	7.4										
28, a. m	143	7.0			239	4.2								
28, a. m	121	8.3	134	7.5	185	5.4								
Aug. 16, a. m							272	3.7						
Sept. 13, a. m							775	1.2	237	4.2				
Oct. 1, a. m	250	4.0												
2, a. m							1,460	0.7						
3, a. m					363	2.8								
12, a. m			180	5.6	160	6.2	272	3.7						
13, a. m					196	5.1	276	3.6	342	2.9				
23, a. m					184	5.4								
25, a. m							500	2.0						
25, a. m							339	2.9						

Temperature—Continued.

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning	....	7.9	....	6.2	....	4.9	....	4.4	....	3.8	....	3.8	....	5.2
Afternoon	....	5.8	....	5.8	....	3.9	....	5.0	....	4.2	....	....	....	4.9
Mean	....	7.6	....	6.1	....	4.8	....	4.5	....	3.9	....	3.8	....	5.1
CLOUDY.														
Morning	....	7.4	....	5.5	....	4.7	....	2.5	....	3.7	....	3.6	....	4.6
Afternoon	....	5.8	....	7.4	....	....	....	6.8	....	6.4	....	....	....	6.6
Mean	....	7.1	....	5.8	....	4.7	....	3.0	....	4.2	....	3.6	....	4.7
COMBINED.														
Morning	....	7.8	....	6.0	....	4.8	....	3.9	....	3.8	....	3.8	....	5.0
Afternoon	....	5.8	....	6.2	....	3.9	....	5.3	....	5.3	....	....	....	5.3
Mean	....	7.5	....	6.0	....	4.7	....	4.1	....	3.9	....	3.8	....	5.0

SAULT STE. MARIE, MICH.

TEMPERATURE.

At Sault Ste. Marie there were in all 74 ascensions and 180 observations at altitudes of 1,000 feet or more, and the greatest altitude attained was 5,607 feet.

The mean decrease of temperature with increase of altitude was 4.9° for each 1,000 feet. The greatest rate was found, as usual, up to 1,000 feet, while the lowest occurred up to 5,000 feet, there being a steady, though by no means regular, decrease with increase of altitude.

The morning gradients were markedly greater than those of the afternoon, except up to 5,000 feet, where it was only 0.4° less. The greatest difference occurred up to 1,000 feet, where it amounted to 4° per 1,000 feet. The afternoon results were greater than the adiabatic rate at all elevations up to 3,000 feet, becoming rapidly smaller beyond. Up to 1,000 feet the gradient was 10°, while up to 5,000 feet it was but 3.4° per 1,000 feet. It should be noted, however, that there were but seven observations at 1,000 feet elevation.

The gradients in clear weather were greater than the cloudy weather ones except up to 5,000 feet, where they were almost exactly alike. The greatest difference again occurs up to 1,000 feet, where it was 3.3° per 1,000 feet.

The presence of clouds as a rule produced the usual effects of suspension of the temperature fall with increase of elevation, at times changing to a slight rise. There would be alternate rises and falls as the kite moved in and out of the clouds, but between very limited extremes, the elevation evidently being without effect as long as clouds were present.

Inversions were very infrequent and of no consequence.

WINDS.

The kite deflections toward the right were frequently quite decided, amounting at one time to 160°, and there were many which equaled or exceeded 90°. The deflections toward the left were only three or four in number and the amount was small. Two of these abnormal deflections were followed by rain within a short time.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity changed but little above the height of 1,500 feet, the extreme range of the mean values from 1,500 to 5,000 feet having been but 5 per cent, the minimum occurring at 4,000 feet and the maximum at 5,000 feet. The humidity at the surface decreased steadily as each day's ascension progressed, and it was higher than those at the different elevations up to 3,000 feet, the greatest difference being 9 per cent at 1,500 feet. Above 3,000 feet the humidity was higher than at the ground, with a difference of 14 per cent at 5,000 feet. Cloud effects were usually well-defined, consisting in a marked rise in the humidity as the kite entered the clouds, generally to above 90 and often to 100 per cent, followed by an equally marked fall as it emerged, the fall sometimes being as much as 35 per cent.

Vapor pressure results are given below. They agree very closely with those at Duluth and Dubuque up to 3,000 feet, but differ from 0.05 to 0.13 above that height.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p^{o}}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.
0.83	0.76	0.71	0.71	0.44

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 4, a. m			483	2.1					285	3.5				
5, a. m			144	6.9										
5, p. m			218	4.6			173	5.8	211	4.7				
5, p. m									120	8.3				
6, p. m			180	5.6	193	5.2	268	3.7						
7, a. m					448	2.2	275	3.6						
8, a. m			343	2.9										
9, p. m			128	7.8					281	3.6				
9, p. m									208	4.8				
10, a. m					154	6.5								
13, a. m			180	5.6										
15, p. m			142	7.0			153	6.5	184	5.4	275	3.6		
16, a. m					385	2.6			481	2.1	539	1.9		
17, a. m					243	4.1	285	3.5						
17, p. m							139	7.2						
24, a. m			197	5.1			222	4.5	268	3.7	274	3.6		
25, p. m			274	3.6										
26, p. m			90	11.1										
30, a. m					203	4.9								
30, a. m					386	2.6								
31, a. m			393	2.5										
June 4, p. m					154	6.5								
8, a. m					194	5.2	234	4.3						
July 15, a. m	122	8.2												
20, a. m					245	4.1			267	3.7				
21, a. m					198	5.1								
23, p. m			79	12.7										
23, p. m			72	13.9	95	10.5								
25, a. m			128	7.8										
27, a. m			92	10.9	117	8.5	165	6.1	172	5.8				
29, a. m							365	2.7						
29, a. m			202	5.0	196	5.1	261	3.8						
31, p. m			179	5.6										
Aug. 4, p. m							175	5.7						
4, p. m					116	8.6	146	6.8						
5, p. m			86	11.8	101	9.9	124	8.1	156	6.4				
8, a. m					168	6.0	179	5.6	245	4.1				
12, a. m					187	4.3	171	5.8						
12, p. m									169	5.9				
26, p. m					171	5.8	136	7.4						
30, a. m							192	5.2	339	2.9				
31, a. m							1,271	0.8	670	1.5				
31, a. m							555	1.8	883	1.1	738	1.4		
31, p. m									790	1.3				
Sept. 1, a. m							159	6.3						
3, a. m			123	8.1			175	5.7	190	5.3	205	4.9		
3, p. m									178	5.6				
11, a. m			286	3.5	346	2.9								
12, a. m					443	2.3	253	4.0						
13, a. m	117	8.5	160	6.2	189	5.3	213	4.7	202	5.0	304	3.3		
18, a. m			172	5.8	193	5.2	252	4.0						
28, a. m			123	8.1	148	6.8	162	6.2						
28, p. m									195	5.1				
28, p. m									247	4.0				
29, a. m	115	8.7			220	4.5	328	3.0	410	2.4	439	2.3		
Oct. 1, a. m			318	3.1					1.165	0.9	491	2.0		
8, a. m					169	5.9	217	4.6	221	4.5	242	4.1		

Temperature—Continued.

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 2, p. m					1,060	0.9								
3, p. m			403	2.5										
12, p. m					500	2.0	299	3.3						
18, a. m							950	1.1			374	2.7		
19, p. m					169	5.9								
20, a. m							207	4.8	370	2.7	217	4.6		
27, a. m					173	5.8								
29, p. m			148	6.8	156	6.4								
June 1, p. m			218	4.6										
3, p. m					363	2.8	425	2.4						
3, a. m									172	5.8	408	2.5		
5, p. m			235	4.3	290	3.4								
6, p. m			176	5.7										
9, p. m	100	10.0												
July 16, a. m	235	4.3	304	3.3	202	5.0								
19, a. m					118	8.5								
Aug. 1, p. m			94	10.6	130	7.7								
13, a. m					191	5.2								
15, a. m			168	6.0										
16, p. m			82	12.2	114	8.8	121	8.3						
17, p. m			120	8.3										
21, p. m			203	4.9	241	4.1	229	4.4						
28, a. m			401	2.5										
29, a. m							195	5.1	282	3.5	327	3.1		
Sept. 9, a. m			215	4.7										
25, a. m					224	4.5	240	4.2	309	3.2				
25, a. m											380	2.6		
30, p. m			143	7.0	194	5.2								
30, p. m					132	7.6								
Oct. 3, p. m					851	1.2								
16, a. m					210	4.8	1,187	0.8	623	1.6				
16, a. m							692	1.4						
23, a. m	235	4.3	240	4.2	192	5.2								
28, a. m	478	2.1	364	2.7										
29, a. m			384	2.6	392	2.6	370	2.7	459	2.2				
29, p. m											327	3.1		

SUMMARY.

CLEAR.

Morning		8.5		6.2		4.7		4.3		3.2		2.9		5.0
Afternoon				7.4		7.8		6.4		5.0		3.6		6.6
Mean		8.5		6.7		5.4		4.9		4.1		3.0		5.4

CLOUDY.

Morning		3.6		3.7		5.2		2.9		3.2		3.1		3.6
Afternoon		10.0		6.7		4.7		4.6				3.1		5.8
Mean		5.2		5.5		4.9		3.5		3.2		3.1		4.2

COMBINED.

Morning		6.0		5.4		4.8		3.9		3.3		3.0		4.4
Afternoon		10.0		7.0		5.7		5.8		5.0		3.4		6.2
Mean		6.6		6.2		5.2		4.5		3.9		3.0		4.9

DODGE CITY, KANS.

TEMPERATURE.

One hundred and thirty-eight ascensions and 573 observations were made at Dodge City at altitudes of 1,000 feet or more, and the greatest altitude attained was 8,019 feet.

The mean temperature decrease was at the rate of 4.2° for each 1,000 feet of ascent. The average decrease from the ground up to 1,000 feet was 6.3°; for the other altitudes it was as follows: Up to 1,500 feet, 5.2° per thousand feet; 2,000 feet, 4.8°; 3,000 feet, 3.7°; 4,000 feet, 3.1°; 5,000 feet, 3.2°; 6,000 feet, 3.2°; 7,000 feet, 3.2°; 8,000 feet, 4.9°. (Plate 3.) These are the general mean values obtained from observations made in all kinds of weather and at all hours between 8 a. m. and 8 p. m., Eastern time. They are somewhat greater than those at Washington up to 4,000 feet, and, as was the case at the latter place, there is a decrease up to this height, and thereafter a practically uniform rate, agreeing almost exactly with the Washington results, except up to 8,000 feet. The difference at 8,000 feet was no doubt largely due to the time of day at which the observations were taken, that at Washington having been taken about 8 a. m., while that at Dodge City was taken in the afternoon. Both days were clear.

The inversions of temperature, of which 52 cases were noted, occurred mostly on clear days with the lighter winds, not often less than 10 miles per hour, however, at the surface, and in two cases over 20 miles. They were at a minimum during May, and gradually increased in number during the remaining months. They quite frequently extended to the height of 3,000 feet, and on one occasion to over 5,000 feet, the inversion in this case amounting to over 11°, or 2.2° per thousand feet.

Inversions were sometimes caused by the formation of clouds in the early morning. Below the clouds there would be little or no change in the temperature, while above there would be an increase on account of the direct action of the sun's rays. The result was, of course, an inversion. A marked case occurred on October 1, when there was a rise in the temperature of 11.5° within a few minutes after the kite emerged from the upper surface of the clouds.

The amount of inversion at Dodge City was in general less than at Washington on account of the higher wind velocities at the former place.

The mean morning gradient was 3.8° per thousand feet, and the same suspension of decrease above 4,000 feet occurs. The greatest gradient was found up to 1,000 feet, where it was 6.4° per thousand feet, and the least, 2.6°, up to 4,000 feet. (Plate 1.)

The afternoon gradient was, of course, much more regular, but, except up to 1,500 feet, lacks the approach to the adiabatic line that characterized the afternoon curve at Washington. The average was 4.7° per thousand feet, 1.3° less than the Washington afternoon figures and 0.7° less than the adiabatic rate. (Plate 2.) Up to 1,500 feet the morning, afternoon, and mean values are very nearly alike, reaching their greatest divergence up to 4,000 feet, and again becoming very nearly equal up to 6,000 and 7,000 feet.

As a rule the presence of clouds produced the usual phenomena of decided decreases in the gradient, at times amounting to a complete, though slight, inversion. On May 16 there was a rise in the temperature of 2.5° while the kite was in the clouds, and a return to the previous reading as soon as the edge of the clouds was reached. On May 25, while the kite was enveloped in cloud, the temperature decrease was but 1° for 2,554 feet of altitude, or 0.4° per thousand feet, while just before reaching the clouds the decrease was 1° in 943 feet, or 1.1° per thousand feet. On May 28, while the kite was at the edge of the clouds, the decrease in temperature was at the rate of 1° in 6,248 feet, or somewhat less than 0.2° per thousand feet, the altitude being 3,124 feet. On August 4, from 8 to 10 a. m., the kite reaching an altitude of 3,700 feet, there was no change in the temperature on account of clouds passing under or over the kite; then a rise of 2.3° at 10.10 a. m. while the kite was above the cloud, followed by a fall of 2° as soon as the clouds were reached in descent, and a corresponding rise when the kite emerged below. In this case the cloud temperature exhibited remarkable uniformity, remaining at about 64° with variations of less than one-half degree. A similar instance of uniformity of cloud temperature occurred on August 17, the variation, while the kite was in or near the clouds, having been but 1°. In a few cases the presence of clouds did not appear to exercise an appreciable effect upon the temperature.

Brisk to high winds were the rule, both above and at the surface, during the entire period in which ascensions were made, and the higher ones were usually, though not uniformly, attended by a decrease in the gradient. The directions of the wind did not appear to have any bearing upon the result.

WINDS.

The wind directions were practically the same above and at the surface, the differences being confined to a deflection of the kite toward the right. Frequently the deflection increased with the altitude, but rarely amounted to more than 90°. In some instances the deflection of the kite was toward the left, but neither frequently nor decidedly, except in one instance. On October 4, the day on which the greatest altitude was attained, the upper and lower winds were about the same, southwest to southwest and south, until shortly after 3 p. m., when the surface wind changed to north, again changing to northeast shortly before 5 p. m. and remaining at that point. The upper wind continued to blow from the southwest until 5 p. m., when it began to shift toward the left, reaching the northeast direction at 5.10 p. m., and again coinciding with the surface wind. The velocity of the upper wind was comparatively light after the surface wind changed to north, and remained so until both again blew from the same direction.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

Generally speaking there was comparatively little change in the relative humidity with changes of elevation except in the few observations above 7,000 feet. Between the limits of 1,500 and 4,000 feet, where more than 90 per cent of the observations were made, the mean decrease was only 5 per cent, and up to 6,000 feet but 10 per cent. The differences between the surface humidities and those at the kite were also quite small. The highest humidities were noted with winds at the surface from north to northeast, and the lowest with those from southeast to west, particularly with those from southeast to south. Approaching rain, or the fact that rain had fallen a few hours previously, appeared to have little or no effect except in a few instances, and in these an equal rise took place at the same time at the surface.

Cloud effects were also comparatively insignificant except on a few days. There would be a slight rise when the kite entered a cloud, usually of 3 or 4 per cent, occasionally of 10, and once of 17 per cent; but at no time did the humidity rise as high as 90 per cent if it had been below that point before the cloud was reached. In one or two cases the humidity fell slightly while the kite was in the clouds, while on October 1 there was a fall of 45 per cent as the kite was leaving the cloud from above. It will be remembered that October 1 was also the day on which occurred the marked temperature inversion above the cloud.

The vapor-pressure results obtained were higher than those at Washington, with the exception of those at 1,500 feet. The figures for both places are given below, and it is readily apparent from an inspection of them that the changes with increase of altitude are much less at Dodge City than at Washington.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

Station.	1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.	8,000 feet.
Dodge City	0.85	0.84	0.80	0.71	0.61	0.56	0.51	0.55
Washington	0.87	0.82	0.66	0.60	0.54	0.46	0.45	0.34

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 2, a. m			2,270	0.4																
6, a. m							270	3.7												
7, p. m					201	5.0	217	4.6												
9, p. m					126	7.9														
10, a. m	109	9.2			166	6.0	169	5.9												
11, a. m	153	6.5	153	6.5	140	7.1	161	6.2	172	5.8										
12, a. m							801	1.2												
18, p. m	119	8.4					159	6.3												
18, p. m							234	4.3												
19, p. m			120	8.3			150	6.7												
21, p. m			154	6.5	182	5.5	180	5.6												
22, p. m	174	5.7	164	6.1																
23, a. m							1,111	0.9	443	2.3										
24, p. m					212	4.7			277	3.6										
27, a. m	250	4.0																		
29, a. m					200	5.0	250	4.0	717	1.4			573	1.7						
30, a. m					576	1.7														
31, a. m							230	4.3			271	3.7								

Temperature—Clear—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 1, p. m			130	7.7			165	6.1												
2, a. m					148	6.8			847	1.2	505	2.0								
2, a. m									309	3.2										
14, p. m	139	7.2																		
19, p. m	112	8.9	131	7.6																
20, a. m	116	8.6	170	5.9	193	5.2	231	4.3												
20, a. m	147	6.8	117	8.5	132	7.6														
21, a. m							1,169	0.9												
21, a. m			317	3.2	446	2.2	425	2.4												
22, a. m	137	7.3	298	3.4	441	2.3	1,207	0.8												
23, a. m			655	1.5	674	1.5	340	2.9	364	2.7	309	3.2	263	3.8						
23, a. m					209	4.8	206	4.9	208	4.8	217	4.6								
23, p. m	190	5.3																		
24, a. m					627	1.6	212	4.7												
25, a. m					2,134	0.5	281	3.6	858	1.2										
25, a. m			148	6.8	170	5.9														
26, a. m	158	6.3	163	6.1	161	6.2														
26, a. m			125	8.0	139	7.2														
27, p. m	150	6.7	154	6.5	167	6.0														
27, a. m			139	7.2																
28, a. m	118	8.5			574	1.7	396	2.5												
28, a. m			135	7.4	150	6.7	261	3.8												
29, a. m							1,343	0.7	460	2.1	368	2.7								
29, a. m	116	8.6	140	7.1	150	6.7	158	6.3	247	4.0										
30, a. m							959	1.0	392	2.6										
30, a. m			133	7.5	164	6.1	257	3.9												
July 1, a. m	129	7.8			404	2.5														
1, a. m			150	6.7	189	5.3														
2, a. m	996	1.0			510	2.0	349	2.9	273	3.7										
2, a. m			128	7.0	130	7.7	155	6.5												
3, p. m	120	8.3	149	6.7																
5, a. m	138	7.2	167	6.0	179	5.6	187	5.3												
5, a. m	114	8.8			143	7.0														
6, a. m							1,029	1.0	464	2.2										
6, a. m	135	7.4	144	6.9			277	3.6	366	2.7										
9, a. m	165	6.1	193	5.2	131	7.6														
9, a. m	119	8.4	125	8.0																
11, a. m	246	4.1	370	2.7	235	4.3														
12, p. m	194	5.2	194	5.2	193	5.2														
12, p. m			172	5.8																
13, p. m	138	7.2																		
13, p. m	146	6.8																		
15, p. m			227	4.4	157	6.4														
16, a. m			252	4.0	250	4.0														
16, a. m	190	5.3	197	5.1																
17, a. m							1,104	0.9	514	1.9	348	2.9								
17, a. m	151	6.6	163	6.1	145	6.9			260	3.8										
19, a. m	170	9.3	206	4.9	475	2.1	1,977	0.5												
20, a. m			164	6.1	205	4.9														
20, a. m			153	6.5																
20, p. m	246	4.1																		
22, a. m			445	2.2																
22, a. m			325	3.1	404	2.5														
23, a. m	514	1.9			251	4.0														
23, p. m			458	2.2	371	2.7														
25, a. m	199	5.0																		
26, a. m	173	5.8	180	5.6	190	5.3	199	5.0												
26, p. m					169	5.9	178	5.6	207	4.8										
28, a. m			1,343	0.7	530	1.9														
28, a. m	130	7.7	315	3.2																
29, a. m			446	2.2			2,533	0.4												
29, a. m			181	5.5	394	2.5	986	1.0												
30, a. m	118	8.5			3,029	0.3	588	1.7												
30, a. m	85	11.8	180	5.6			336	3.0												
Aug. 8, a. m							683	1.5	287	3.5										
8, a. m					177	5.6	215	4.7												
10, a. m	239	4.2	289	3.5																
12, a. m			1,313	0.8	527	1.9	450	2.2	305	3.3										
12, a. m	122	8.2			203	4.9	252	4.0												
13, a. m	107	9.3	186	5.4					1,057	0.9										
15, a. m	247	4.0																		
16, a. m					2,175	0.5														
19, a. m	295	3.4	283	3.5	244	4.1	254	3.8												
19, p. m	138	7.2	198	5.1																
20, a. m	122	8.2			227	4.4	318	3.2												
21, a. m			260	3.8	258	3.9	220	4.5												
21, p. m	181	5.5			194	5.2														
22, a. m	126	7.9	168	6.0	225	4.4	273	3.7	377	2.7										
23, a. m	171	5.8							699	1.4										
23, a. m			269	3.7	462	2.2	418	2.4	429	2.3										
24, a. m			435	2.3	404	2.5	363	2.8												
24, a. m	153	6.5	245	4.1																
25, p. m			191	5.2																
26, p. m	144	6.9																		
27, p. m			172	5.8	189	5.3														
28, a. m	208	4.8	363	2.8	413	2.4	937	1.1												
29, a. m	148	6.8	215	4.7	140	7.1	241	4.1												
30, a. m									980	1.1	343	2.9	247	4.0						

Temperature—Clear—Continued

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Aug. 30, a. m.	144	6.9	161	6.2			155	6.7	197	5.1	231	4.3								
31, a. m.	150	6.7	173	5.8	200	5.0	370	2.7												
Sept. 1, a. m.					338	3.0	478	2.1												
1, a. m.	153	6.5	208	4.8	252	4.0														
2, a. m.	161	6.2	180	5.6	751	1.3	1,427	0.7												
3, a. m.									1,147	0.9										
3, a. m.	120	8.3	156	6.4	177	5.6	299	3.3	468	2.1										
4, a. m.											689	1.5	433	2.3	330	3.0				
4, a. m.	121	8.3	115	8.7					255	3.9	284	3.5	296	3.4						
5, a. m.			260	3.8					2,152	0.5	596	1.7								
5, a. m.	106	9.4	144	6.9			305	3.3	348	2.9										
7, p. m.	380	2.6	401	2.5	741	1.3														
8, a. m.			771	1.3	708	1.4	357	2.8	311	3.2										
8, a. m.	143	7.0	143	7.0	143	7.0	192	5.2												
14, p. m.	354	2.8	306	3.3	222	4.5	200	3.8												
14, p. m.					214	4.7	243	4.1												
17, a. m.	067	1.5	1,188	0.8																
20, a. m.			258	3.9	202	5.0	226	4.4	240	4.2										
20, a. m.					164	6.1	175	5.7												
21, a. m.			528	1.9	402	2.5	265	3.8	253	4.0										
21, p. m.	108	9.3			170	5.9	161	6.2												
22, a. m.	258	3.9																		
23, a. m.	150	6.7			196	5.1	192	5.2	198	5.1	199	5.0								
23, a. m.					228	4.4														
23, p. m.					159	6.3	184	5.4												
27, p. m.			190	5.3	172	5.8	179	5.6	200	5.0										
27, p. m.	236	4.2	212	4.7	198	5.1														
28, a. m.	195	5.1	149	6.7	150	6.7	340	2.9	904	1.1										
29, p. m.	122	8.2	135	7.4	147	6.8														
29, p. m.					172	5.8														
29, p. m.			126	7.9	146	6.8														
30, a. m.			264	3.8	270	3.7														
30, a. m.					661	1.5	472	2.1	213	4.7	277	3.6	304	3.3						
30, p. m.	128	7.8	133	7.5			180	5.6												
Oct. 1, a. m.	136	7.4																		
2, a. m.	133	7.5	299	3.3																
3, a. m.	525	1.9																		
4, a. m.									2,758	0.4										
4, p. m.											297	3.4	253	4.0						
4, p. m.													228	4.4	286	3.5	204	4.9		
4, p. m.	159	6.3	360	2.8					1,635	0.6			345	2.9						
4, p. m.	167	6.0																		
5, a. m.	118	8.5	133	7.5	239	4.2	1,310	0.8												
6, p. m.			180	5.6	197	5.1	192	5.2			348	2.9	446	2.2						
6, p. m.	2,364	0.4			294	3.4	333	3.0	311	3.2	515	1.9								
9, a. m.									1,866	0.5	250	4.0								
9, p. m.			214	4.7	243	4.1	238	4.2												
10, p. m.			155	6.5	159	6.3														
10, p. m.			142	7.0																
11, p. m.	145	6.9	159	6.3	154	6.5	177	5.6	202	5.0	201	5.0								
11, p. m.					506	2.0	313	3.2	249	4.0										
12, a. m.			148	6.8	152	6.6	116	8.6	304	3.3	1,624	0.6								
14, a. m.	118	8.5	122	8.2	146	6.8	264	3.8												
15, a. m.									2,310	0.4	658	1.5								
15, p. m.	109	9.2	148	6.8	151	6.6	184	5.4	315	3.2	358	2.8								
18, a. m.							1,034	1.0												
18, a. m.							506	2.0												
18, a. m.	176	5.7	179	5.6	196	5.1	354	2.8												
20, a. m.							590	1.7	738	1.4	654	1.5								
20, a. m.	164	6.1	176	5.7	208	4.8	195	5.1	312	3.2										
21, p. m.	144	6.9	166	6.0	147	6.8														
21, p. m.					160	6.2														
23, a. m.			147	6.8	162	6.2	386	2.6	901	1.1	2,068	0.5								
23, p. m.	133	7.5																		
24, a. m.	203	4.9																		
24, a. m.	159	6.8																		
26, p. m.							233	4.3	296	3.4										
26, p. m.											298	3.4								
26, p. m.											231	4.3								
26, p. m.							183	5.5	186	5.4										
27, a. m.							439	2.3	285	3.5										
27, p. m.	136	7.4	139	7.2	151	6.6			161	6.2										
28, a. m.							166	6.0	193	5.2	185	5.4								
28, p. m.					141	7.1			190	5.3										
29, a. m.							1,147	0.9	396	2.5										
29, a. m.	140	7.1			216	4.6	272	3.7												
30, a. m.			152	6.6	183	5.5	222	4.5												
30, p. m.									181	5.5	202	5.0								
30, p. m.	113	8.8			151	6.6	139	7.2	167	6.0										
31, a. m.	137	7.3	172	5.8																
31, a. m.	134	7.5																		

Temperature—Continued.

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		8,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 1, p. m.	272	3.7																		
4, p. m.	221	4.5																		
5, p. m.			216	4.6																
14, a. m.							375	2.7			286	3.5								
15, p. m.	148	6.8	170	5.9																
16, a. m.	587	5.3	397	2.5																
17, a. m.			488	2.0																
25, a. m.			943	1.1																
26, p. m.	120	8.3			215	4.7														
28, a. m.							1,558	0.6												
June 3, a. m.									1,689	0.6										
3, a. m.							156	6.4	394	2.5										
5, p. m.	189	5.3	238	4.2	213	4.7														
6, p. m.			232	4.3																
6, p. m.			209	4.8																
8, p. m.	272	3.7																		
9, p. m.	144	6.9	133	7.5																
24, a. m.	152	6.6																		
25, a. m.	120	8.3																		
July 21, a. m.	147	6.8	167	6.0	171	5.8														
21, a. m.			130	7.7																
22, p. m.	442	2.3																		
31, a. m.	171	5.8	193	5.2	183	5.5														
31, a. m.			154	6.5	186	5.4														
Aug. 3, p. m.			144	6.9	169	5.9	189	5.3												
3, p. m.	108	9.3			124	8.1														
4, a. m.							803	8.2	548	1.8										
4, a. m.	127	7.9	167	6.0	258	3.9	360	2.8												
4, a. m.	93	10.8																		
7, a. m.	243	4.1	271	3.7	259	3.9	330	3.0	228	4.4										
7, a. m.	103	9.7	141	7.1			190	5.3												
17, a. m.	807	1.2																		
17, a. m.	221	4.5																		
17, a. m.	333	3.0																		
18, a. m.	2,086	0.5																		
18, a. m.	683	1.5																		
18, a. m.	238	4.2																		
Sept. 19, a. m.			137	7.3	173	5.8														
19, p. m.	162	6.2																		
Oct. 1, a. m.			1,451	0.7																
1, a. m.	236	4.2	165	6.1																
9, p. m.									167	6.0										
10, p. m.	139	7.2																		
12, p. m.	126	7.9																		
19, p. m.	183	5.5	195	5.1	205	4.9	292	3.4	314	3.2										
19, p. m.			1,071	0.9	469	2.1	360	2.8												
21, p. m.			165	6.1	173	5.8	186	5.4	196	5.1	220	4.5								

SUMMARY.

CLEAR.

Morning		6.7		5.0		4.4		3.2		2.7		2.9		3.1		3.0				3.9
Afternoon		6.3		5.8		5.4		5.2		4.4		3.6		3.4		3.5		4.9		4.7
Mean		6.6		5.3		4.7		3.7		3.1		3.1		3.2		3.2		4.9		4.2

CLOUDY.

Morning		5.3		4.8		5.0		4.8		2.3										4.4
Afternoon		6.0		5.0		5.2		3.4		4.8		4.5								5.8
Mean		5.6		4.9		5.1		4.2		3.4		4.5								4.6

COMBINED.

Morning		6.4		5.0		4.5		3.3		2.6		2.9		3.1		3.0				3.8
Afternoon		6.2		5.6		5.4		4.8		4.4		3.7		3.4		3.5		4.9		4.7
Mean		6.3		5.2		4.8		3.7		3.1		3.2		3.2		3.2		4.9		4.2

Temperature—Continued.

INVERSIONS.

CLEAR.

Date.	800 feet.		1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.		2,500 feet.		3,000 feet.		3,500 feet.		4,000 feet.		4,500 feet.		5,000 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 8, a. m					666	1.5																
12, a. m											409	2.4										
12, a. m											2,739	0.4										
28, a. m			432	2.3							1,557	0.6										
30, a. m									395	2.5												
30, a. m									446	2.2												
31, a. m							522	1.9	515	1.9												
31, a. m							616	1.6														
June 21, a. m							289	3.5	469	2.1												
24, a. m							566	1.8														
24, a. m							844	1.2	978	1.0												
25, a. m													1,841	0.5								
29, a. m									459	2.2	2,168	0.5										
30, a. m											1,149	0.9										
July 6, a. m									567	1.8	3,330	0.3										
18, a. m					286	3.5	274	3.6	276	3.6												
18, a. m					197	5.1	439	2.3	336	3.0												
19, a. m											716	1.4	4,046	0.2								
22, 9 p. m							1,092	0.9														
27, a. m							156	6.4	222	4.5	472	2.1	357	2.8								
27, a. m							1,054	0.9	500	2.0	654	1.5	497	2.0								
Aug. 8, a. m			281	3.6	562	1.8	783	1.3														
13, a. m					662	1.5	1,723	0.6			926	1.1	365	2.7			1,055	0.9				
15, a. m					109	9.2	142	7.0	164	6.1												
15, a. m									221	4.5	278	3.6	496	2.0								
15, a. m					1,876	0.5			775	1.3	975	1.0	899	1.1								
16, a. m							228	4.4			588	1.7	379	2.6								
20, a. m											1,517	0.7										
22, a. m									287	3.5	488	2.0	1,619	0.6								
23, a. m									578	1.7	551	1.8	2,189	0.5								
28, a. m											463	2.2										
28, a. m											895	1.1	5,020	0.2								
30, a. m											332	3.0	676	1.5	1,573	0.6						
31, a. m											412	2.4	1,486	0.7								
Sept. 1, a. m											430	2.3	1,981	0.5								
2, a. m	347	2.9							386	2.6	920	1.1										
3, a. m															1,700	0.6						
4, a. m													471	2.1	2,783	0.4	6,407	0.2				
5, a. m									1,072	0.9			1,036	1.0								
7, 8 p. m							321	3.1														
17, a. m							216	4.6	268	3.7												
24, a. m							117	8.5	137	7.3	151	0.7										
24, a. m					207	4.8			245	4.1												
28, a. m													380	2.6	728	1.4	879	1.1				
29, a. m	150	6.7			192	5.2																
Oct. 2, a. m					2,570	0.4	1,245	0.8	1,357	0.7	418	2.4	2,787	0.4								
3, a. m					106	9.4	130	7.7														
4, 5 p. m											431	2.3	629	1.6	875	1.1						
5, a. m									1,262	0.8	777	1.3										
6, 7 p. m	385	2.6																				
11, 7 p. m	283	3.5																				
12, a. m									181	5.5	260	3.8										
14, a. m									227	4.4	564	1.8	1,299	0.8								
15, a. m													586	1.7								
18, a. m															765	1.3	966	1.0				
23, a. m																	374	2.7	460	2.1	451	2.2
29, a. m							216	4.6	478	2.1	646	1.5	1,969	0.5								
31, a. m									164	6.1	192	5.2										
31, a. m									1,988	0.5												
CLOUDY.																						
June 4, 8 p. m			514	1.9																		
Aug. 14, a. m					731	1.4	499	2.0	360	2.8	432	2.3	1,446	0.7								
14, a. m							1,322	0.8			2,465	0.4										
17, a. m			544	1.8	741	1.3																
Oct. 1, a. m							257	3.9	351	2.8			441	2.3								

DUBUQUE, IOWA.

TEMPERATURE.

Of the Dubuque series 148 observations at altitudes of 1,000 feet or more were examined. The number of ascensions was 65, and the greatest altitude attained, 5,065 feet.

The mean gradient was found to be 4.6° per thousand feet. There is a steady and quite uniform decrease from 1,000 up to 3,000 feet, and a further slight decrease up to 4,000 feet, followed by a slight increase thereafter. The greatest gradient was 6.9°, and the least, 3.2° per thousand feet. Up to 3,000, 4,000, and 5,000 feet they agree almost exactly with those at Omaha.

The average morning and afternoon and the mean gradients were exactly equal, but the two former varied irregularly up to the different elevations. This station was one of the four at which the afternoon gradient did not nearly equal or exceed the adiabatic rate, the other three being Dodge City, Springfield, and Duluth.

Except up to 1,000 feet, the clear-weather gradients were at all elevations considerably greater than the cloudy ones. The greatest difference occurred up to 1,500 feet, where the clear-weather gradient was 7°, and the cloudy one, 4.8° per thousand feet.

The cloud effects, when at all noticeable, were quite dissimilar to those previously experienced in the western country. Instead of a retardation of the temperature fall, the usual effect was an acceleration. Thus, on May 31 there was a fall of 7° from 2,400 to about 3,000 feet of elevation, the kite being in the clouds at the latter height, followed by a rise of 14° as the kite descended to the base of the low clouds at 1,000 feet elevation. On June 11 there was a fall of 7.5° as the kite disappeared in the clouds, with only about 100 feet increase in altitude, and a slow rise as the kite descended.

In the few instances in which the kite ascended above the clouds there was not the usual sharp rise at the place of emergence and a slower fall than usual thereafter, but, instead, a slow rise which in no case exceeded 4°, and which did not extend for more than 1,000 or 1,100 feet above the top of the clouds.

The inversions of temperature were infrequent, and presented no features of especial interest.

WINDS.

The wind directions conformed steadily to the usual rule. There were very few deflections toward the left, and none in either direction was at all marked.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity changes with difference of altitude were very small, the greatest, 8 per cent, being found at 4,000 feet, and the least, 1 per cent, at 2,000 and 3,000 feet. From 2,000 to 4,000 feet there is a steady and regular decrease, followed by a sharp rise of 13 per cent at 5,000 feet. At all altitudes the humidities were higher than at the surface, except at 4,000 feet, at which height was also found the greatest departure from the surface humidity.

The effects of the presence of clouds upon the relative humidity were very much the same as at other stations. There would be a decided rise in most cases as the kite came near or into the clouds, at one time amounting to 33 per cent, followed by a fall as the kite was freed from cloud influence, but not to an equal extent.

The vapor pressure results agree almost exactly with those at Duluth, and maintain a steady relation with those at Dodge City, averaging 0.04 lower.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.
0.83	0.79	0.76	0.66	0.56

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate	Gradient.	Rate.	Gradient.
May 26, p. m	165	6. 1												
June 2, p. m			176	5. 7										
3, a. m					143	7. 0	275	3. 6						
3, p. m	174	5. 7	130	7. 7										
4, p. m	122	8. 2	167	6. 0	207	4. 8								
10, p. m			177	5. 6	157	6. 4								
13, p. m	188	5. 3	160	6. 2										
18, a. m	152	6. 6	139	7. 2	246	4. 1								
19, a. m	130	7. 7	114	8. 8										
20, a. m	143	7. 0												
21, a. m					1, 039	9. 6								
21, a. m					191	5. 2								
25, a. m					280	3. 6	360	2. 8						
27, a. m					163	6. 1								
28, p. m			159	6. 3										
July 5, p. m			124	8. 1	145	6. 9								
6, a. m					249	4. 0	211	4. 7						
6, a. m			142	7. 0	117	8. 5	163	6. 1						
8, p. m			176	5. 7										
17, a. m					253	4. 0								
17, a. m					163	6. 1								
18, a. m							509	2. 0	263	3. 8				
20, a. m							813	1. 2	518	1. 9	438	2. 3		
20, a. m					181	5. 5	272	3. 7						
28, a. m			113	8. 8										
Aug. 5, p. m					174	5. 7	198	5. 1						
5, p. m					190	5. 3	185	5. 4						
10, a. m					459	2. 2	224	4. 5						
11, a. m					199	5. 0	209	4. 8	183	5. 5				
11, p. m			124	8. 1	120	8. 3	151	6. 6						
12, a. m					150	6. 7	164	6. 1						
22, a. m			139	7. 2										
Sept. 1, a. m							277	3. 6	202	5. 0	179	5. 6		
2, p. m					378	2. 6	316	3. 2	257	3. 9				
2, p. m							162	6. 2	200	5. 0	230	4. 3		
19, a. m			134	7. 5										
21, a. m							302	3. 3	288	3. 5				
21, p. m							226	4. 4						
28, a. m					732	1. 4	438	2. 3						
28, p. m					237	4. 2	280	3. 6						
29, a. m							547	1. 8	317	3. 2	238	4. 2		
29, p. m							189	5. 3	220	4. 5				
Oct. 24, a. m					1, 039	1. 0								
24, a. m					440	2. 3								
26, a. m			162	6. 2	194	5. 2								
31, a. m							445	2. 2						
31, p. m									806	1. 2	793	1. 3		
31, p. m									1, 316	0. 8				

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate	Gradient.	Rate.	Gradient.
May 20, p. m	97	10. 3												
27, a. m	212	4. 7												
29, p. m	171	5. 8	139	7. 2										
31, a. m	133	7. 5			114	8. 8								
31, p. m			104	9. 6										
June 1, a. m			171	5. 8										
5, p. m	86	11. 6	147	6. 8										
9, p. m	272	3. 7	252	4. 0	237	4. 2								
11, a. m	110	9. 1			245	4. 1								
14. a. m	157	6. 4	181	5. 5			331	3. 0						
15, a. m							990	1. 0						
15, a. m							400	2. 5						
15, p. m			152	6. 6			274	3. 6						
22, a. m							374	2. 7						
22. a. m			293	3. 4	442	2. 3								
23, a. m			375	2. 7	452	2. 2								
23, a. m					220	4. 5								
24, a. m					1, 065	0. 9	440	2. 3						
26, p. m	372	2. 7												
30, a. m			958	1. 0										
30, a. m			551	1. 8										
Aug. 2, p. m	198	5. 1	167	6. 0										
6, a. m					999	1. 0	293	3. 4						
15, a. m			235	4. 3										
16, a. m	134	7. 5	236	4. 2	1, 102	0. 9								
Sept. 3, a. m			576	1. 7										
6, a. m							663	1. 5	543	1. 8	560	1. 8		
6, a. m							213	4. 7	301	3. 3				
12, a. m	100	10. 0												
14, a. m							369	2. 7	318	3. 1	306	3. 3		

Temperature—Cloudy—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Oct. 5, a. m.					155	6.5								
6, p. m.			161	6.2										
7, a. m.					295	8.4								
9, p. m.					204	4.9								
16, a. m.					913	1.1								
22, a. m.					164	6.1								
23, p. m.							983	1.0						
27, p. m.							624	1.6	842	1.2				

SUMMARY.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		7.1		7.6		5.1		3.5		3.8		4.0		5.2
Afternoon		6.3		6.4		5.0		5.0		3.1		2.8		4.8
Mean		6.7		7.0		5.1		4.0		3.5		3.5		5.0

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		7.5		3.4		3.5		2.6		2.7		2.6		3.7
Afternoon		6.5		6.6		4.6		2.1		1.2				4.2
Mean		7.0		4.8		3.6		2.5		2.4		2.6		3.8

COMBINED.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		7.4		5.4		4.4		3.2		3.5		3.4		4.6
Afternoon		6.4		6.5		4.9		4.2		2.8		2.8		4.6
Mean		6.9		5.9		4.6		3.5		3.2		3.3		4.6

NORTH PLATTE, NEBR.

TEMPERATURE.

In the North Platte observations 524 were considered at altitudes of 1,000 feet or more, and of these, 216 were taken in the morning and 308 in the afternoon. The highest altitude attained was 5,600 feet and the number of ascensions was 132.

The mean gradient was found to be 5.6° per thousand feet. This is much greater than those at Dodge City and Omaha. The rate up to 1,000 feet was 6.8°, and up to the remaining elevations as follows: Up to 1,500 feet, 6.5° per thousand feet; 2,000 feet, 5.9°; 3,000 feet, 5.2°; 4,000 feet, 4.4°, and 5,000 feet, 4.7°. (See plate 1.)

There is, as is usual in this district, a decrease up to 4,000 feet and an increase thereafter, and the rate of increase and decrease was quite regular.

The morning curve closely parallels the mean, while the afternoon one occupies a similar position on the opposite side of the mean, and at almost equal distances from it.

The clear-weather gradients were greater than the cloudy ones except up to 1,000 feet, the greatest difference being found up to 1,500 feet, where it was 1° per thousand feet.

The cloud effects were, as a rule, confined to a partial or complete suspension of the temperature fall. At times there was a rise, followed by a fall as soon as the kite emerged, and in about one-half the cases the clouds appeared to exercise little or no effect. None was sufficiently marked to be worthy of special note except on June 30, when a remarkable inversion due to clouds took place. The sky was partially overcast with clouds, and fresh east to east-southeast winds were blowing at the surface, inclining somewhat to the right above, with moderate velocities, as indicated by the pull on the kite wire. At 600 feet elevation there was one-half degree rise in the temperature, but at 1,500 feet the excess amounted to 5°, and steadily increased to 13.5° at 3,000 feet. The temperature at the kite rose 17.5° with increase of height to 3,000 feet, while that at the surface rose but 3.5° during the same time, which was from 7.25 to 8.45 a. m. The day previous had been quite warm, and the upper air had become warmed to a considerable extent.

The clear night had promoted surface radiation, and the early cloud formation, by cutting off the sun's heat in the morning, prevented the usual readjustment. The cloud dissipated about 8.45 a. m., and then occurred a sudden rise in the surface temperature of 12°, and a gradual return thereafter to somewhat normal conditions.

The inversions were comparatively few and without special characteristics except in the one instance of June 30, which has just been described. On August 4 there was a rise of 12.5° between 1,900 and 2,600 feet as the kite emerged above a cloud, accompanied by a fall in the humidity of 30 per cent. As soon as the cloud had moved away the temperature fell 10°, and the humidity rose 21 per cent, although the kite had fallen 400 feet.

The wind direction and velocity appeared to exercise no effect. It is true that the gradients were, as a rule, much greater with west, particularly northwest, than with east winds, but the east winds were generally associated with cloudy weather, and the decreased gradients at these times must be attributed to the presence of the clouds.

WINDS.

Wind directions followed the usual rule of deflection toward the right, and to about the same extent as at Omaha, but less than at Dodge City. Movements in the opposite direction were infrequent and not decided, and in a majority of cases were followed by rain and thunderstorms.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity conformed to the general rule of steady decrease with increase of altitude, but there is a departure from the rule in that the humidity above is uniformly greater than that at the ground, being 3 per cent greater at 1,500 feet, and increasing slowly to 7 per cent at 5,000 feet. It is suggested that this increase is due to the preponderance of west to north winds, which, with their lower temperatures, cause a rise in the relative humidity, the quantity of moisture in the atmosphere remaining approximately the same.

Cloud effects were indifferent and irregular. In a majority of cases the proximity of rain produced no effect either way. Occasionally there would be a rise previous to the commencement of rain, at one time amounting to 28 per cent, but such cases were very rare. The presence of the kite in the clouds was also without event, except in the one case of August 4. As a rule the only effect was to maintain the humidity at a nearly stationary point, without regard to altitude or time of day. On August 4, as noted before, as the kite emerged above a cloud there was a fall of 30 per cent in the humidity, due to a rise in the temperature of 12.5°, and a rise of 21 per cent as the kite descended after the cloud had disappeared, the temperature falling 10° at the same time.

The vapor pressure results are given below. It will be noticed that they agree almost exactly with the Omaha results between 3,000 and 5,000 feet.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p_0}$ FOR EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.
0.78	0.72	0.66	0.57	0.40

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 7, a. m.			95	10.5	103	9.7								
7, p. m.			69	14.5	115	8.7	139	7.2	162	6.2				
8, p. m.			83	12.0	91	11.0	113	8.8	138	7.2	152	6.6		
10, a. m.			105	9.5	154	6.5	137	7.3						
10, p. m.			116	8.6			142	7.0						
11, a. m.			216	4.6	266	3.8	210	4.8	197	5.1	180	5.6		
11, p. m.									174	5.7				
18, p. m.			133	7.5	161	6.2								
21, a. m.	276	3.6	404	2.5										
21, p. m.	154	6.5	149	6.7	170	5.9	163	6.1	158	6.3				
23, a. m.			438	2.3	334	3.0	294	3.4						
29, a. m.	140	7.1	404	2.5	271	3.7								
30, p. m.			360	2.8										
June 1, a. m.	149	6.7												
1, p. m.			140	7.1	157	6.4	263	3.8						
2, p. m.	187	5.3	248	4.0										
3, p. m.	67	14.9	139	7.2	143	7.0	160	6.2						
8, a. m.	123	8.1												
12, p. m.	187	5.3												
15, p. m.			438	2.3										
19, p. m.	106	9.4	110	9.1	106	9.4	130	7.7						
20, a. m.			113	8.8	129	7.8								
21, p. m.	500	2.0												
22, p. m.	139	7.2	173	5.8	168	6.0	214	4.7	200	5.0				
23, a. m.									771	1.3	397	2.5		
23, a. m.			133	7.5	163	6.1	217	4.6	349	2.9				
25, p. m.	138	7.2	146	6.8	152	6.6	173	5.8						
26, a. m.	1.658	0.6	622	1.6	170	5.9	208	4.8						
26, a. m.			164	6.1										
27, p. m.			139	7.2	143	7.0								
29, a. m.	273	3.7	229	4.4	268	3.7								
July 1, a. m.	126	7.9												
2, a. m.	236	4.2												
4, p. m.			141	7.1	135	7.4	171	5.8						
5, a. m.	216	4.6	160	6.2	157	6.4								
5, a. m.	121	8.3												
10, p. m.	134	7.5	117	8.5										
11, a. m.	130	7.7	194	5.2	226	4.4								
12, p. m.	106	9.4	133	7.5	194	5.2	171	5.8						
13, a. m.	126	7.9	228	4.4	249	4.0	249	4.0	202	5.0				
13, p. m.			106	9.4	124	8.1	149	6.7						
14, a. m.	263	3.8	142	7.0	188	5.3								
15, a. m.	127	7.9	129	7.8										
16, p. m.			117	8.5	124	8.1								
17, a. m.	136	7.4			525	1.9	389	2.6	277	3.6				
17, p. m.			121	8.3	236	4.2	321	3.1						
18, p. m.	103	9.7	167	6.0	178	5.6	176	5.7						
19, a. m.			172	5.8	187	5.3	265	3.8						
10, a. m.	184	5.4	213	4.7										
20, p. m.			118	8.5	139	7.2	165	6.1						
21, a. m.			973	1.0	815	1.2	343	2.9						
21, p. m.			118	8.5	135	7.4	202	5.0						
22, p. m.	127	7.9	134	7.5	142	7.0	161	6.2						
23, p. m.			153	6.5	165	6.1	148	6.8						
24, a. m.	106	9.4	141	7.1	150	6.7								
26, p. m.	132	7.6												
26, p. m.			146	6.8	139	7.2	174	5.7						
27, a. m.			172	5.8	190	5.3	235	4.3						
27, p. m.			132	7.6	145	6.9	168	6.0						
28, a. m.			161	6.2	190	5.3	177	5.6						
28, p. m.					129	7.8	180	5.6						
29, a. m.			160	6.2										
Aug. 3, a. m.			180	5.6	141	7.1	197	5.1						
3, p. m.			120	8.3										
5, a. m.	84	11.9	418	2.4	408	2.5	391	2.6						
9, a. m.	106	9.4	135	7.4	175	5.7	197	5.1	201	5.0				
15, p. m.	120	8.3	143	7.0	143	7.0								
16, a. m.			350	2.9	513	1.9	858	1.2						
16, p. m.									286	3.5				
17, p. m.	127	7.9	159	6.3	154	6.5								
18, p. m.	174	5.6												
19, a. m.			156	6.4										
20, p. m.	2,222	0.5	537	1.9	276	3.6	251	4.0						
21, p. m.			161	6.2	154	6.5	175	5.7						
21, p. m.			144	6.9	174	5.7								
26, p. m.	94	10.6												
27, a. m.									1,324	0.8				
27, a. m.			95	10.6	117	8.5	141	7.1	190	5.3				
28, a. m.	100	10.0	137	7.3	134	7.5	169	5.9						
28, p. m.			102	9.8	112	8.9								
29, p. m.	90	11.1	145	6.9	132	7.6	154	6.5						
30, a. m.			153	6.5	199	5.0	202	5.0	247	4.0				
30, p. m.			116	8.6	127	7.9	139	7.2						
Sept. 1, a. m.	109	9.2			938	1.1	150	6.7						
1, a. m.			132	7.6	137	7.3								
2, p. m.	117	8.5	135	7.4	135	7.4								

Temperature—Clear—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Sept. 4, p. m.			91	11.0	115	8.7	140	7.1						
4, p. m.			97	10.3	86	11.6								
6, a. m.			161	6.2	157	6.4	170	5.9	176	5.7				
6, p. m.			80	12.5	100	10.0	114	8.8						
7, p. m.	81	12.3	99	10.1	125	8.8	144	6.9						
8, a. m.							943	1.1						
8, p. m.			92	10.9			118	8.5						
17, p. m.			130	7.7	139	7.2	157	6.4						
19, p. m.	161	6.6	170	5.9	182	5.5								
19, p. m.			148	6.8										
20, a. m.							651	1.5	516	1.9	243	4.1		
20 p. m.					134	7.5	184	5.4	190	5.2				
21, a. m.	189	5.3	169	5.9										
22, p. m.	185	5.4	191	5.2	199	5.0								
22, p. m.	291	3.4												
23, p. m.	193	5.2	214	4.7	222	4.5	201	5.0						
23, p. m.			269	3.7										
24, p. m.	117	8.5	137	7.3										
26, p. m.	125	8.0	128	7.8										
27 a. m.			135	7.4	478	2.1	360	2.8	402	2.5	291	3.4		
27, p. m.							222	4.5	170	5.9	227	4.4		
29, p. m.	353	2.8												
30, a. m.			144	6.9	266	3.8	149	6.7						
30, p. m.			86	11.6	107	9.3								
Oct. 2, a. m.			116	8.6	141	7.1	144	6.9	150	6.7	198	5.1		
2, p. m.			97	10.3	123	8.1	124	8.1						
4, p. m.			140	7.1	122	8.2	139	7.2	163	6.1				
4, p. m.			150	6.7	156	6.4	168	6.0						
10, a. m.			149	6.7	196	5.1	226	4.4	195	5.1				
12, a. m.			232	4.3										
12, a. m.			122	8.2										
13, p. m.	117	8.5	107	9.3	124	8.1	167	6.0						
14, p. m.			256	3.9	211	4.7	263	3.8						
14, p. m.					763	1.3								
18, p. m.			206	4.9	162	6.2	184	5.4	307	3.3				
18, p. m.			382	2.6	230	4.3	268	3.7						
19, p. m.			479	2.1	408	2.5	405	2.5						
21, p. m.	176	5.7	155	6.5	125	8.0								
21, p. m.			87	11.5										
23, p. m.			229	4.4	199	5.0	219	4.6	259	3.9				
23, a. m.									349	2.9				
25, a. m.			146	6.8	161	6.2	214	4.7	249	4.0	226	4.4		
25, p. m.			83	12.0	80	12.5	137	7.3	159	6.3	107	5.1		
26, p. m.			108	9.3	127	7.9	176	5.7	187	5.3				
27, p. m.			128	7.8	147	6.8	146	6.8	183	5.5	187	5.3		
27, p. m.			90	11.1	99	10.1	129	7.8	147	6.8	163	6.1		
28, a. m.			152	6.6	175	5.7								
28, p. m.							222	4.5	207	4.8				
28, p. m.			104	9.6	121	8.3	141	7.1	174	5.7				
29, p. m.			111	9.0	171	5.8								
29, p. m.			157	6.4										
29, p. m.			172	5.8										
30, p. m.			114	8.8	157	6.4	159	6.3	292	3.4				
30, p. m.			398	2.5	265	3.8	256	3.9						
CLOUDY.														
May 1, a. m.			239	4.2	245	4.1	304	3.3						
1, p. m.			133	7.5	141	7.1								
2, p. m.			105	9.5										
3, p. m.			149	6.7	202	5.0	209	4.8						
4, p. m.			185	5.4	216	4.6	265	3.8						
5, a. m.	242	4.1	290	3.4	338	3.0								
5, p. m.			135	7.4	152	6.6	167	6.0						
12, p. m.			203	4.9	123	8.1	150	6.7						
13, a. m.			180	5.6	192	5.2	238	4.2	343	2.9				
13, p. m.							171	5.8						
14, p. m.			146	6.8										
15, a. m.	310	3.2	404	2.5										
15, p. m.	280	3.6	373	2.7	245	4.1								
16, p. m.			190	5.3	201	5.0	220	4.5						
17, a. m.			210	4.8	189	5.3	163	6.1	232	4.3	252	4.0		
20, a. m.	258	3.9												
23, p. m.			252	4.0	321	4.1	210	4.8						
24, a. m.							1,258	0.8						
24, p. m.	205	4.9	180	5.6										
25, a. m.	185	5.4	214	4.7										
26, a. m.	126	7.9	146	6.8	184	5.4								
27, a. m.	224	4.5	193	5.3	242	4.1	224	4.5						
28, a. m.	682	1.5	1,259	0.8										
28, p. m.	146	6.8	182	5.5										
31, a. m.	180	5.6	157	6.4										
June 4, p. m.	212	4.7	308	3.2	287	3.2								
9, p. m.			283	3.5	302	3.3								
10, a. m.	248	4.0	173	5.8	252	4.0								
14, a. m.	809	1.2	1,021	1.0	1,364	0.7								
14, p. m.			234	4.3	217	4.6								
30, a. m.			130	7.7	152	6.6	735	1.4	1,208	0.8				

Temperature—Cloudy—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradi ent.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
July 8, p. m	93	10.8	175	5.7	142	7.0								
9, a. m			278	3.6	469	2.1	299	3.3						
9, p. m			143	7.0	148	6.8								
11, p. m			156	6.4	129	7.8								
Aug. 1, a. m			209	4.8	228	4.4	191	5.2						
4, a. m			183	5.5	154	6.5								
4, a. m			96	10.4										
23, a. m			255	3.9	239	4.2								
23, p. m			121	2.4										
Sept. 10, p. m			206	4.9	313	3.2	290	3.4	306	3.3				
10, p. m			228	4.4	202	5.0	300	3.3						
16, p. m	71	14.1	108	9.3	119	8.4								
Oct. 3, a. m			215	4.7	830	1.2	663	1.5	550	1.8				
3, p. m			110	9.1	139	7.2	215	4.7	405	2.5				
9, a. m			279	3.6										
9, p. m			126	7.9										
15, p. m			164	6.1	155	6.5	167	6.0	212	4.7	239	4.2		
15, p. m			251	4.0	202	5.0	224	4.5	215	4.7				
16, a. m			232	4.3	176	5.7	204	4.9	190	5.3				
16, p. m			112	8.9	153	6.5	164	6.1						
20, a. m	100	10.0	150	6.7	180	5.6	250	4.0	270	3.7				
24, a. m	110	9.1	166	6.0	202	5.0	347	2.9						

SUMMARY.

CLEAR.

Morning		6.8		6.2		5.0		4.5		3.9		4.2		5.1
Afternoon		7.3		7.3		7.0		5.9		5.8		5.5		6.7
Mean		7.1		6.9		6.3		5.4		4.6		4.8		5.8

CLOUDY.

Morning		5.0		4.9		4.6		3.5		3.1		4.0		4.2
Afternoon		7.5		5.9		5.4		5.0		3.8		4.2		5.3
Mean		5.8		5.4		5.1		4.3		3.4		4.1		4.7

COMBINED.

Morning		6.2		5.7		4.8		4.2		3.7		4.2		4.8
Afternoon		7.3		7.0		6.6		5.7		5.0		5.3		6.0
Mean		6.8		6.5		5.9		5.2		4.4		4.7		5.6

INVERSIONS.

Date.	600 feet.		800 feet.		1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.		2,500 feet.		3,000 feet.		3,500 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 30									302	3.3	195	5.1	253	4.0	223	4.5		
Aug. 12, 9 p. m			1,638	·0.6			2,816	0.4										
27									118	8.5	141	7.1	190	5.3	263	3.8	317	3.2
Sept. 1									941	1.1								
8									1,532	0.7	4,152	0.2						
20									525	1.9								
Oct. 14									1,061	0.9								
23									141	7.1	306	3.3			630	1.6		

OMAHA, NEBR.

TEMPERATURE.

There were considered of the Omaha series of observations 185, obtained from 61 ascensions, and the greatest altitude attained was 7,243 feet.

The general mean decrease of temperature with increase of altitude was at the rate of 4.1° for each 1,000 feet. The average decrease up to 1,500 feet was 5.4°; up to the other elevations it was as follows: up to 2,000 feet, 4.9° per thousand feet; 3,000 feet, 3.6°; 4,000 feet, 3.2°; 5,000 feet, 3.5°; 6,000 feet, 3.8°, and 7,000 feet, 4.1°. (See plate 1.) There is the usual decrease up to 4,000 feet, and a steady increase thereafter. The change is most rapid between 2,000 and 3,000 feet.

The morning gradients averaged 3.6° per thousand feet, 0.5° less than the mean. The curve fairly parallels the mean curve, the greatest difference being found at 2,000 and the least at 6,000 feet. The afternoon mean was 5.9° per thousand feet, and from 4,000 feet upward is very close to the true adiabatic rate, averaging 5.3° per thousand feet. The greatest gradient was up to 1,500 feet, where it was 7.1° per thousand feet. The clear-weather gradients were naturally greater than the cloudy ones, particularly up to 2,000 feet, where the difference was 1.4° per thousand feet. An exception occurs up to 5,000 feet; but as there was but a single observation made at that height during cloudy weather, a fair comparison can not be had.

Cloud effects were much the same as at other stations, though not in so marked a degree as at some. There would be a sudden check in the temperature fall, and often a change to a rise, amounting at one time, August 19, to 5° between 1,500 and 2,200 feet of altitude. Other slight rises were noted, and there were still other cases in which the clouds, while not of sufficient influence to cause a rise in the temperature, would hold it steady until the kite emerged. No cases of inversion due to clouds were noticed.

The inversions of temperature were very few, on account of the time of day at which the major portion of the observations were taken.

WIND.

The wind directions conformed to the usual rule, being practically alike above and at the surface. There was the usual deflection of the kite toward the right, but to a lesser degree than at Dodge City or Washington. There were very few deflections in the opposite direction, and none was at all marked.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The change in the relative humidity with elevation was quite decided, a steady decrease being the rule up to the highest elevations reached. At 1,500 feet the relative humidity was 4 per cent higher than at the ground; at 2,000 feet it was 1 per cent lower; at 4,000 feet, 12 per cent lower; at 5,000 feet, 19 per cent lower; at 6,000 feet, 28 per cent lower, and at 7,000 feet, 34 per cent lower.

Clouds and the close proximity of rain, either before or after the ascensions, exercised a very pronounced effect upon the humidity, the rise being rapid and decisive. At times it amounted to as much as 30 or 40 per cent, and on one day to 51 per cent. On this day, September 20, there was a belt of cloud at an altitude of about 4,500 feet, and as the kite reached it from above there was a rise in the humidity from 35 to 86 per cent, followed by a steady fall after the kite emerged.

The vapor pressure results follow. It will be noticed that there is a rapid diminution above 2,000 feet, corresponding to the marked decrease in the relative humidity with increase of altitude.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUTE.

VALUE OF $\frac{p}{p_0}$ FOR EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.	7,000 feet.
0.83	0.80	0.68	0.56	0.39	0.23	0.15

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 17, a. m...			1,021	1.0	259	3.9												
17, a. m...			475	2.1														
18, p. m...			123	8.1	151	6.6												
20, a. m...					700	1.4	300	8.3										
22, a. m...									175	5.7								
23, a. m...									1,344	0.7	707	1.4						
23, a. m...											813	3.2						
23. p. m...							183	5.5	180	5.6								
24, a. m...					145	6.9	485	2.1										
26, a. m...					2,016	0.5	593	1.7										
26, a. m...					585	1.7												
27, a. m...									917	1.1	498	2.0						
28, a. m...					628	1.6			309	3.2								
29, a. m..					176	5.7	474	2.1	383	2.6								
Aug. 4, a. m...					652	1.5	257	3.9	259	3.9								
4, a. m...			123	8.1	134	7.5	190	5.3										
6, p. m...					179	5.6												
6, p. m...					140	7.1												
8, a. m...			600	1.5	211	4.7												
9, a. m...							214	4.7	218	4.6								
9, a. m...					146	6.8	211	4.7										
10, a. m...							833	1.2	1,073	0.9	1,003	1.0	436	2.3				
10, a. m...									191	5.2	293	3.4						
11, a. m...			177	5.6	178	5.6	244	4.1	253	4.0								
14, p. m...					231	4.3	229	4.4										
15, a. m...			128	7.8	142	7.0												
17, a. m...					194	5.2												
19, p. m...			119	8.4	129	7.8												
22, a. m...							1,582	0.6										
22, a. m...					161	6.6	180	5.6										
24, p. m...			155	6.5	131	7.6												
28, a. m...			155	6.5	217	4.6	375	2.7	339	2.9								
30, a. m...			245	4.1	520	1.9												
31, a. m...			125	8.0	126	7.9	141	7.1	619	1.6	216	4.6	307	3.3				
Sept. 1, a. m...							491	2.0	445	2.2	301	3.3	212	4.7				
1, p. m...									159	6.3	174	5.7						
2, a. m...									988	1.0	501	2.0						
2, a. m...											226	4 4						
3, a m...					163	6.1												
4, a. m...									389	2.6								
4. p. m...			110	8.4	118	8.5	141	7.1										
5, a. m...							443	2.3	252	4.0								
6. p. m...					118	8.5					165	6.1						
7, a. m...									1,140	0.9	587	1.7						
7, p. m...									175	5.7								
8, p. m...			163	6.1	136	7.4	206	4.9										
18, a. m...							371	2.7	425	2.4	423	2.4						
19, p. m...			226	4.4	202	5.0	193	5.2										
20, a. m...							165	6.4	303	3.3	213	4.7	246	4.1	205	4.9		
20, p. m...													188	5.3				
20, p. m...					138	7.2												
21, a. m...							762	1.3	521	1.9	221	4.5						
21, p. m...							134	7.5	193	5.2								
23, a. m...									495	2.0	482	2.1	362	2.8	303	3.3		
23, p. m...			260	3.8	250	4.0			208	4.8	321	3.1						
24, a. m...							1,003	1.0										
24, a. m...			276	3.6	250	4.0	288	3.5										
27, a. m...					729	1.4												
27, p. m...					185	5.4												
28, p. m...									201	5.0	201	5.0						
28, p. m...			88	11.4					162	6.2								
Oct. 5, a. m...					146	6.8	446	2.2	1,964	0.5								
13, a. m...					159	6.3	669	1.5	493	2.0								

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 14, a. m.........					329	3.0	190	5.3										
21, a. m.........			559	1.8	500	2.0	704	1.4										
Aug. 2, p. m.........			162	6.2	192	5.2												
5, a. m.........			142	7.0	193	5.2	314	3.2										
19, a. m.........							421	2.4										
20, a m.......					657	1.5												
23, p. m.........			127	7.9			390	2.6										
Sept. 5, p. m.........					193	5.2	215	4.7	250	4.0								
6, a. m.........					673	1.5	456	2.2										
9, a. m.........					216	4.7	266	3.8	297	3.4								
9, a. m.........			274	3.6			452	2.2										
11, a. m.........							453	2.2	363	2.8								
11, a. m.........							178	5.6										
13, p. m.........					132	7.6	157	6.4										

Temperature—Cloudy—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		7,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Sept. 14, a. m.					359	2.8	366	2.7										
16, a. m.			297	3.4	331	3.0	385	2.6	807	1.2								
20, p. m.											158	6.3						
Oct. 19, a. m.					262	3.8	291	3.4										
19, a. m.			215	4.7	197	5.1	228	4.4										
20, a. m.					277	3.6												
21, a. m.			164	6.1														
27, a. m.			613	1.6														
29, a. m.			165	6.1														
30, a. m.			256	3.9														
SUMMARY.																		
CLEAR.																		
Morning				4.8		4.6		3.0		2.6		2.9		3.4		4.1		3.6
Afternoon				7.1		6.5		6.9		5.5		5.0		5.3				6.0
Mean				5.9		5.3		3.7		3.3		3.4		3.8		4.1		4.2
CLOUDY.																		
Morning				4.2		3.3		3.2		2.5								3.3
Afternoon				7.0		6.0		4.6		4.0		6.3						5.6
Mean				4.8		3.9		3.4		2.8		6.3						4.2
COMBINED.																		
Morning				4.6		4.2		3.1		2.6		2.9		3.4		4.1		3.6
Afternoon				7.1		6.4		6.0		5.4		5.2		5.3				5.9
Mean				5.4		4.9		3.6		3.2		3.5		3.8		4.1		4.1

PIERRE, S. DAK.

TEMPERATURE.

Four hundred and sixteen observations at altitudes of 1,000 feet or more were considered in computing the temperature gradients at Pierre; the number of ascensions was 134, and the highest altitude attained 6,059 feet. The mean gradient was found to be 4.6° for each thousand feet of ascent, 0.5° greater than that at Omaha, 1.0° less than that at North Platte, and the same as that at Dubuque.

Contrary to the usual experience at stations in this district, the decrease with increase of elevation disappears above 3,000 feet instead of above 4,000 feet, and is again resumed above the latter elevation, the minimum gradient being found up to 6,000 feet.

The inversions of temperature were for the most part confined to the usual conditions in such cases, namely, clear mornings and the radiation effects resulting therefrom. None were decidedly marked except in the month of September. On the 20th of this month there was an inversion of 16° at an elevation of 1,677 feet, or at the rate of 9.5° per thousand feet, at 8.16 a. m., and at 3,500 feet at 8.37 a. m. there was still an inversion of 6°, or at the rate of 1.7° per thousand feet. It did not entirely disappear until after the 4,000 foot level had been passed at 9.03 a. m. On September 23, during a cloudy morning, there was an inversion of 15.4° at an elevation of 3,050 feet, or at the rate of 5° per thousand feet, at 7.54 a. m., the excess above the surface temperature increasing with the altitude up to this point. The inversion was still 11.3° at 3,400 feet, or at the rate of 3.3° per thousand feet, and did not finally disappear until about 10 a. m., after the kite had passed up beyond the 4,000-foot level.

These inversions, of which twenty-four instances were found, occurred with but three exceptions on days when a low barometric area was central to the northwestward, causing warm southerly winds which were usually brisk.

More than two-thirds of the observations were taken in the morning, and the average morning gradient was 4.3° per thousand feet, 0.3° less than the mean, and 0.7° greater than that at Omaha. There are no great divergences from the mean curve, the maximum difference, 0.6° per thousand feet, occurring up to 1,000 feet.

The afternoon average was 6.3° for each thousand feet, 0.9° greater than the adiabatic rate. The rate of decrease was greater at all elevations than the adiabatic rate, and was 2.1° greater up to 1,000 feet. The clear weather gradients were greater than the cloudy ones, the mean difference being 0.9° per thousand feet. The afternoon means show the least difference. The greatest difference occurred up to 4,000 feet, where it was 2.6°, and the least up to 1,500 feet, where it was 0.5° per thousand feet. In both clear and cloudy weather the greatest gradients were found up to 1,000 feet, and the least up to 4,000 feet. An extremely large gradient was noted during the afternoon of September 26, when it was 13° up to 1,000 feet, and 10.5° per thousand feet up to 1,500 feet.

The clouds at times appeared to exercise considerable effect, and at others little or none. The usual result was a retardation of the temperature fall. On one date there was a fall of 4° as the kite reached the clouds, the elevation remaining practically the same while the temperature was falling. On June 22 there was a rise of 12° as the kite emerged above the clouds, and a much slower rate of fall thereafter, amounting to but 5.7° in 2,600 feet of ascent. There is evidence of a similar action on September 30 at 1,900 feet elevation, although no reference to clouds can be found. On October 2 the temperature commenced to rise when the clouds were reached, and rose 8° while the kite ascended from 1,700 to 2,700 feet. From thence up to 5,000 feet the usual decrease took place.

WINDS.

There were very few cases of kite deflection toward the left. Only two were noticeable to any extent, and rain fell shortly afterwards in both instances. The amount of deflection toward the right was also less than was usually observed, the directions above and at the surface being practically the same.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The changes with altitude in the relative humidity were very slight. In fact, it may be said that there was practically none. The extreme range was but 8 per cent, the highest humidity, 66 per cent, being found at 3,000 feet, and the lowest, 58 per cent, at 5,000 feet. The percentage at 6,000 feet was 64, but it is very probable that these comparatively high figures are due to the scarcity of observations at that level and that a greater number would have shown a decrease in the mean.

As at North Platte, the upper-air humidities were uniformly greater than those at the surface, the greatest differences being 15 per cent at 5,000 feet and 16 per cent at 6,000 feet, and the least, 5 per cent at 2,000 feet.

The preponderance of easterly winds, with their greater moisture content, may have some bearing upon this fact. Nearly 52 per cent of the winds were from some easterly direction, and 30 per cent were from the southeast.

The proximity of rain caused a rise in the humidity, as a rule, to some point above 80 or 85 per cent, the surface humidity showing a less rise, and in some instances a fall. During the summer months low humidities of course prevailed, and rain did not exercise so great an influence.

The clouds quite frequently caused a rise to total saturation as the kite reached them. At other times their effect was not so marked, but at all times was greater than at the remaining stations in this district.

The vapor pressure results, as given below, show a greater agreement between the amount of moisture above and at the surface than is usual, and correspond closely to the slight differences in the relative humidity before noted. They are greater at all altitudes than those at North Platte and Omaha, and are even greater than those at Dodge City, except at 3,000 feet, where there is a difference of 5 per cent in favor of the latter.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p^{\circ}}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.
0.90	0.86	0.75	0.72	0.69	0.69

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 15, p. m			146	6.8	168	6.0										
23, p. m			162	6.2	147	6.8	227	4.4	234	4.3						
24, a. m							441	2.3	311	3.2						
25, p. m	179	5.6			141	7.1	147	6.8								
27, a. m	113	8.8			132	7.6	133	7.5								
27, p. m					149	6.7	146	6.8								
30, a. m	309	3.2			265	3.8	171	5.8	199	5.0	253	4.0	271	3.7		
31, a. m			149	6.7	194	5.2	244	4.1								
June 1, a. m					158	6.3	184	5.4								
5, a. m			443	2.3	122	8.2										
8, p. m	261	3.8	463	2.2												
11, p. m	192	5.2	295	3.4												
13, a. m			99	10.1	124	8.1	126	7.9								
16, p. m			273	3.7	314	3.2										
17, a. m			108	9.3	119	8.4	142	7.0								
17, p. m									148	6.8	161	6.2				
19, a. m	545	1.8	608	1.6			520	1.9	269	3.7	209	4.8				
20, a. m	796	1.3	377	2.7	538	1.9	612	1.6	234	4.3						
21, a. m			1,658	0.6					344	2.9	250	4.0				
23, a. m	132	7.6	148	6.8	185	5.4	239	4.2	394	2.5	312	3.2	225	4.4		
26, a. m	173	5.8	228	4.4												
27, p. m	108	9.3	118	8.5	146	6.8	153	6.5								
28, a. m	432	2.3	395	2.5												
29, a. m	98	10.2	116	8.6	142	7.0	157	6.4	144	6.9	170	5.9				
July 4, a. m	129	7.8	133	7.5	140	7.1										
5, a. m	158	6.3	178	5.6	196	5.1	162	6.2								
6, a. m	109	9.2	117	8.5	155	6.5	162	6.2								
8, p. m	164	6.1														
10, a. m	578	1.7	655	1.5	416	2.4	364	2.7	325	3.1						
11, p. m	140	7.1	152	6.6	180	5.6										
12, p. m	121	8.3														
13, a. m			298	3.4	855	1.2	586	1.7	314	3.2	328	3.0				
14, a. m	919	1.1					554	1.8	242	4.1						
15, a. m	156	6.4	173	5.8	160	6.2	173	5.8								
16, p. m	134	7.5	140	7.1	160	6.2	165	6.1								
17, a. m	766	1.3	495	2.0												
18, a. m					621	1.6	215	4.7								
19, a. m	332	3.0	372	2.7	366	2.7										
20, p. m	99	10.0	103	9.7	140	7.1	149	6.7	153	6.5	173	5.8				
21, a. m									2,399	0.4	592	1.7				
22, a. m	1,042	1.0														
24, a. m	143	7.0	162	6.2	179	5.6	244	4.1	218	4.6	242	4.1				
25, a. m	133	7.5	128	7.8												
26, a. m							1,089	0.9	626	1.6						
27, a. m	215	4.7					783	1.4								
28, a. m	124	8.1	146	6.8	170	5.9	164	6.1	173	5.8						
29, a. m	106	9.4	140	7.1	156	6.4										
Aug. 1, p. m	110	9.1														
2, p. m	106	9.4	116	8.6												
3, a. m	116	8.6	123	8.1	133	7.5										
4, a. m	357	2.8	463	2.2	1,018	1.0	565	1.8								
6, p. m	207	4.8														
7, a. m	119	8.4	128	7.8												
8, a. m	424	2.4	422	2.4	387	2.6										
9, a. m	415	2.4	410	2.4	1,939	0.5	694	1.4	353	2.8						
10, a. m	153	6.5	155	6.5												
13, a. m							365	2.7								
15, a. m	115	8.7			157	6.4	124	8.1								
16, a. m	877	1.1	570	1.8	1,125	0.9	1,178	0.8								
18, a. m	347	2.9	269	3.7												
20, a. m	111	9.0	118	8.4	144	6.9										
22, a. m	120	8.3	133	7.5												
23, a. m	123	8.1	123	8.1	133	7.5	227	4.4	280	3.6	235	4.3				
24, p. m	120	8.3	135	7.4												
26, a. m	127	7.9	162	6.2	237	4.2										
29, a. m					1,063	0.9	451	2.2	308	3.2	215	4.7				
30, a. m	198	5.1	436	2.3	808	1.2										
30, a. m			181	5.5	202	5.0										
31, a. m	132	7.8	123	8.1												
Sept. 1, a. m	477	2.1	430	2.3	266	3.8										
3, a. m			750	1.3	473	2.1										

Temperature—Clear—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Sept. 4, p.m.	89	11.5			115	8.7	141	7.1								
5, a.m.	147	6.8	172	5.8	179	5.6										
6, a.m.	934	1.1	646	1.5	486	2.1	328	3.0	237	4.2						
7, a.m.	122	8.2	126	7.9	124	8.1	146	6.8	155	6.5	157	6.4				
12, a.m.	164	6.1	183	5.5	178	5.6	192	5.2	235	4.3	227	4.4				
14, p.m.	139	7.2														
16, a.m.			188	5.3	185	5.4	190	5.3	189	5.3	191	5.2				
18, p.m.	941	1.1	287	3.5	252	4.0										
19, a.m.							506	1.8								
20, a.m.											190	5.3				
22, a.m.	88	11.4														
24, a.m.	109	9.2	131	7.6	144	6.9	211	4.7								
26, p.m.	77	13.0	95	10.5	112	8.9	130	7.7								
28, a.m.	325	3.1	261	3.8	256	3.9	212	4.7	312	3.2						
30, a.m.			655	1.5			1,017	1.0	413	2.4	272	3.7				
Oct. 1, a.m.	225	4.4	213	4.7							225	4.4				
2, a.m.	283	3.5	261	3.8	288	3.5										
6, a.m.	165	6.1	191	5.2	257	3.9	230	4.3	292	3.4						
10, a.m.	162	6.2	183	5.5	187	5.3										
13, a.m.			149	6.7												
25, a.m.	143	7.0	143	7.0	170	5.9										
26, a.m.					447	2.2										
27, a.m.	257	3.9	230	4.3	422	2.4	383	2.6	314	3.2						
28, p.m.	171	5.8	153	6.5	140	7.1	175	5.7	193	5.2						
29, a.m.	602	1.7	2,568	0.4	1,212	0.8	721	1.4	507	2.0						
CLOUDY.																
May 13, p.m.			225	4.4	222	4.5	255	3.9								
14, p.m.					153	6.5										
16, a.m.			376	2.7	217	4.6										
17, p.m.			316	3.2												
18, a.m.			196	5.1	223	4.5										
20, a.m.	195	5.1														
21, a.m.			165	6.1	170	5.9										
26, a.m.			340	2.9												
26, a.m.			176	5.7												
28, a.m.			127	7.9	138	7.2										
29, p.m.	85	11.8														
June 3, a.m.			352	2.4												
3, p.m.					164	6.1	188	5.3								
4, a.m.					331	3.0	381	2.6								
9, p.m.	129	7.8	128	7.8	155	6.5										
12, a.m.	457	2.2														
12, a.m.	218	4.0	151	6.6												
14, a.m.			239	4.2	291	3.4	184	5.4								
15, a.m.			185	5.4												
22, a.m.	200	5.0	151	6.6	191	5.2			1,368	0.7	409	2.4				
24, a.m.	175	5.7	200	5.0	240	4.2	210	4.8	231	4.3	232	4.3				
30, a.m.	1,228	0.8	910	1.1	1,020	1.0	485	2.1	308	3.2						
July 1, a.m.	127	7.9	125	8.0												
2, a.m.	202	5.0	195	5.1	212	4.7	269	3.7	228	4.4	273	3.7				
7, a.m.					409	2.4										
9, a.m.	662	1.5	944	1.1	752	1.3	427	2.3	299	3.3						
23, a.m.			286	3.5	382	2.6	390	2.6	381	2.6						
30, a.m.	227	4.4	252	4.0	133	7.5										
Aug. 5, p.m.	160	6.2	133	7.5	239	4.2										
12, p.m.	111	9.0	116	8.6	139	7.2										
14, a.m.	152	6.6														
17, a.m.	396	2.5	502	2.0	593	1.7	253	6.5	213	4.7						
21, a.m.			1,696	0.6	596	1.7										
Sept. 8, a.m.	254	3.9	290	3.4	324	3.1	344	2.9								
13, p.m.	146	6.8	167	6.0												
29, a.m.	278	3.6	306	3.3	246	4.1										
Oct. 2, a.m.							470	2.1	446	2.2						
4, p.m.	182	5.5	195	5.1												
12, a.m.	318	3.1	265	3.8	291	3.4	271	3.7	381	2.6						
14, a.m.							1,167	0.9								
15, a.m.	220	4.5	214	4.7	286	3.5	236	4.2								
20, a.m.	128	7.8	144	6.9	161	6.2	203	4.9								
21, a.m.	182	5.3	185	5.4												
23, p.m.	155	6.5	141	7.1	174	5.7										
24, a.m.	170	5.9	192	5.2	247	4.0	269	3.7								
SUMMARY. CLEAR.																
Morning		5.5		5.0		4.6		4.0		3.7		4.3		4.0		4.4
Afternoon		7.4		6.5		6.5		6.4		5.7		6.0				6.4
Mean		6.0		5.3		5 0		4.5		3.9		4.5		4.0		4.7

Temperature—Continued.

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		4.5		4.4		3.9		3.5		3.1		3.5				3.8
Afternoon		7.7		6.2		5.8		4.6								6.1
Mean		5.3		4.8		4.4		3.6		3.1		3.5				4.1

COMBINED.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
Morning		5.3		4.8		4.3		3.9		3.5		4.2		4.0		4.3
Afternoon		7.5		6.4		6.2		6.1		5.7		6.0				6.3
Mean		5.9		5.1		4.8		4.3		3.7		4.4		4.0		4.6

INVERSIONS.

Date.	1,000 feet.		1,200 feet.		1,500 feet.		2,000 feet.		2,500 feet.		3,000 feet.		3,500 feet.		4,000 feet.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 23			162	6.2												
24					192	5.2			2,451	0.4						
June 19							2,956	3.4								
21					1,658	0.6	1,594	0.6								
July 7			1,272	0.8												
14			910	1.1	3,932	0.3										
18	1,566	0.6														
21			250	4.0	326	3.1	994	1.0								
26	277	3.6			553	1.8	484	2.1								
27					1,530	0.7	1,304	0.8								
Aug. 11	523	1.9														
13			232	4.3	299	3.3	406	2.5								
19					231	4.3										
27			173	5.8												
Sept. 19			109	9.2	188	5.3	206	4.9	365	2.7						
20			786	1.3	104	9.6	139	7.2	222	4.5	346	2.9	585	1.7	5,014	0.2
21					1,268	0.8										
23			125	8.0	167	6.0	180	5.6	173	5.8	198	5.1	302	3.3	748	1.3
27			403	2.5	328	3.0	277	3.6								
30							1,913	0.5								
Oct. 9			215	4.7	221	4.5	290	3.4								
14			202	5.0	257	3.9	348	2.9								
26			223	4.5	232	4.3	547	1.8								
30	309	3.2			295	3.4	371	2.7								

TOPEKA, KANS.

TEMPERATURE.

The mean gradient at Topeka was 5° per thousand feet, as determined from 319 observations made during 81 ascensions. The highest altitude attained was 5,892 feet. The gradient is greatest up to 1,000 feet, and decreases steadily up to 4,000 feet, above which height it rises slowly. The decrease up to 3,000 feet is quite rapid.

The average morning gradient was 0.5° less than the mean, and decreased at about the same rate with increasing altitude. The average afternoon gradient was 1° greater than the mean, and the decrease with increase of elevation was less decided than in the morning. The clear weather gradients were greater than the cloudy ones at all elevations, but the differences were not marked except up to 2,000 and 4,000 feet, where they were 1.3° and 1.4°, respectively, per thousand feet.

Wind directions and the relative positions of high and low barometric areas did not appear to have had any effect upon the gradients. Cloud effects were confined to a suspension of the temperature fall, changing frequently to a rise, and followed by a fall as the kite descended below the clouds. There were no records of any ascents above the tops of clouds. On October 3 the temperature rose 6° while the kite was rising from 1,700 feet elevation to 2,250 feet at the clouds;

then there was a fall of 6° as the kite descended below the clouds to 1,600 feet. A second ascent to another cloud at 2,000 feet resulted in a rise of 4°, followed by a fall of 5° as the kite descended to 1,400 feet. On October 9 the temperature fell but 1° in rising from 2,900 to 4,200 feet on account of the presence of clouds.

There were several cases of temperature inversion that are worthy of notice. On May 24 there was an inversion of 11° at 2,400 feet elevation, and of 7.5° at 3,650 feet. On August 3 there was an inversion from 7.13 until 10.02 a. m. up to 3,250 feet elevation, amounting to 10° at 1,500 feet at 9.56 a. m. This inversion was due to cloud formation shortly after sunrise, and still continued after the kite had broken away at 10.05 a. m. On October 5 there was an inversion of 3° in the early morning up to 3,000 feet as the clouds cleared away, thus permitting unobstructed radiation from the surface of the earth to the lower air layers.

WINDS.

The deflections of the kite due to winds were invariably toward the right, but the general directions above and below were at all times almost exactly alike, a deflection of as much as 90° occurring but once or twice.

RELATIVE HUMIDITY AND VAPOR PRESSURE.

The relative humidity changes with increase of elevation were very small, the only differences of consequence occurring at 1,500 and 2,000 feet, where they were 8 and 5 per cent respectively, the upper air humidity being the higher. Above 2,000 feet the values are practically equal, the only differences being 1 per cent.

The approach of rain within a few hours was sometimes indicated by a rise in the upper air humidity without a corresponding change in that below, the rise usually bringing the humidity above 90 per cent. Quite frequently, however, the proximity of rain did not appear to exercise the slightest effect.

The cloud effects were not at all marked, the only noticeable one being a slight rise at times. On one day, May 2, there was a fall of 54 per cent (from 94 to 40 per cent) as the kite came near the clouds.

The vapor pressure results as given below agree very nearly with those at Omaha below 5,000 feet. Above this altitude the latter are 0.13 smaller. At 2,000, 3,000, and 4,000 feet the two are exactly alike.

DIMINUTION OF VAPOR PRESSURE WITH ALTITUDE.

VALUE OF $\frac{p}{p^{o}}$ AT EACH RESPECTIVE 1,000 FEET OF ALTITUDE.

1,500 feet.	2,000 feet.	3,000 feet.	4,000 feet.	5,000 feet.	6,000 feet.
0.85	0.80	0.68	0.56	0.52	0.36

TEMPERATURE.

CLEAR.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 6, a. m					1,494	0.7	667	1.5	353	2.8	273	3,7	222	4.5		
6, p. m									209	4.8	190	5.3				
6, p. m							168	6.0	166	6.0						
8, a. m					156	6.4	184	5.4								
11, a. m	73	13.7	101	9.9	113	8.8										
11, a. m							134	7.5	135	7.4	213	4.7				
11, a. m											345	2.9				
11, a. m											261	3.8				
12, a. m			160	6.2												
14, a. m			174	5.7												
18, a. m	232	4.3														
23, a. m					327	3.1	292	3.4								
23, p. m							161	6.2	222	4.5						
24, p. m	119	8.4	114	8.8												
29, p. m					149	6.7	157	6.4	197	5.1						

Temperature—Clear—Continued.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
June 2, p. m.			149	6.7	172	5.8										
3, a. m.					672	1.5	377	2.7								
22, a. m.			1,597	0.6												
22, a. m.			536	1.9	474	2.1	300	3.3								
22, a. m.							210	4.8								
23, a. m.					781	1.3	601	1.7								
23, a. m.	111	9.0	142	7.0			233	4.3								
24, a. m.	127	7.9	164	6.1	271	3.7	217	4.6								
25, a. m.	129	7.8														
27, a. m.	241	4.1														
28, a. m.	123	8.1	144	6.9	124	8.1										
29, a. m.	139	7.2			417	2.4	339	2.9								
29, a. m.							225	4.4								
30, a. m.	192	5.2	120	8.3	199	5.0	263	3.8								
July 1, a. m.			142	7.0	643	1.6	431	2.3								
2, a. m.	144	6.9	189	5.3	171	5.8	541	1.8								
6, p. m.	164	6.1	185	5.4	276	3.6	264	3.8								
9, a. m.	154	6.5														
17, a. m.	91	11.0														
18, a. m.			163	6.1	222	4.5										
18, p. m.	118	8.5														
19, a. m.			444	2.3	147	6.8	800	1.2								
19, a. m.	131	7.6	134	7.5												
27, a. m.	106	9.4	139	7.2	141	7.1	215	4.7								
27, p. m.	72	13.9	108	9.3	140	7.1	140	7.1								
29, p. m.			180	5.6												
Aug. 4, p. m.	139	7.2			154	6.5	163	6.1								
5, p. m.	91	11.0	127	7.9	150	6.5	161	6.2								
5, p. m.	139	7.2			159	6.3										
6, a. m.	94	10.7	132	7.6	203	4.0	248	4.0								
10, p. m.	120	8.3	170	5.9	230	4.3										
14, a. m.	132	7.6	180	5.6	401	2.5	399	2.5	229	4.4	234	4.3				
15, a. m.	102	9.8			524	1.9										
15, p. m.			106	9.4												
16, a. m.	156	6.4	302	3.3	410	2.4	269	3.7								
16, p. m.	104	9.6			113	8.8										
20, p. m.			152	6.6	173	5.8	151	6.6								
20, p. m.	201	5.0			210	4.8	229	4.4								
22, a. m.	565	1.8			504	2.0	369	2.7								
22, p. m.	132	7.6	154	6.5	158	6.3	183	5.5								
23, a. m.									1,176	0.9						
23, p. m.	111	9.0	110	9.1	146	6.8	211	4.7								
28, a. m.					159	6.3	251	4.0								
28, p. m.	155	6.5	148	6.8												
29, a. m.	154	6.5	431	2.3	294	3.4										
29, p. m.			139	7.2	159	6.3										
30, a. m.	480	2.0			778	1.3	449	2.2								
30, a. m.					207	4.8										
31, a. m.					361	2.8	216	4.6								
Sept. 1, a. m.							790	1.3	551	1.8						
1, p. m.	111	9.0	114	8.8	134	7.4	228	4.4								
3, a. m.							200	5.0								
3, p. m.	99	10.1	108	9.3	135	7.4										
5, p. m.	116	8.6	150	6.7	154	6.5										
8, a. m.					399	2.5	146	6.8								
8, a. m.			110	9.1	150	6.7										
9, a. m.	139	7.2	173	5.8												
23, a. m.							1,027	1.0	217	4.6						
23, p. m.	114	8.8			155	6.5										
28, a. m.	114	8.8	185	5.4	262	3.8	247	4.0	226	4.4	202	5.0				
28, p. m.	118	8.5	152	6.6	168	6.0	171	5.8	188	5.3						
29, a. m.							805	1.2	174	5.7						
29, p. m.	110	9.1	133	7.5	138	7.2	156	6.4								
Oct. 2, a. m.							1,120	0.9								
2, p. m.	102	9.8	133	7.5	152	6.6	185	5.4								
4, p. m.	111	9.0	125	8.0												
5, a. m.	299	3.3			505	1.9	593	1.6								
5, p. m.			116	8.6												
9, a. m.	135	7.4			150	6.7	162	6.2	207	4.8						
10, p. m.	136	7.4	126	7.9												
13, a. m.	1,714	0.6			944	1.1	752	1.3	367	2.7	329	3.0				
13, p. m.	139	7.2	138	7.2	182	5.5	181	5.5	230	4.3						
14, a. m.	161	6.2	174	5.7	194	5.2	199	5.0								
14, p. m.			642	1.6	310	3.2										
15, a. m.	200	5.0					1,084	0.9	325	3.1						
29, p. m.	136	7.4	156	6.4	186	5.4	223	4.5	250	4.0	242	4.1				
29, p. m.	260	3.8					167	6.0								
30, p. m.	211	4.7	214	4.7												

Temperature—Continued.

CLOUDY.

Date.	1,000 feet.		1,500 feet.		2,000 feet.		3,000 feet.		4,000 feet.		5,000 feet.		6,000 feet.		Mean.	
	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.	Rate.	Gradient.
May 2, a. m					206	4.9	333	3.0	800	1.2						
2, a. m									973	1.0						
10, p. m									221	4.5						
13, p. m	205	4.9														
17, a. m			1,638	0.6			851	1.2	575	1.7	282	4.5				
17, a. m									243	4.1						
19, p. m	171	5.8	191	5.2												
20, a. m					357	3.8										
21, a. m			215	4.7												
21, a. m			179	5.6												
26, a. m					249	4.0	230	4.3								
27, a. m	103	9.7			146	6.8										
31, a. m							1,818	0.6	793	1.3	531	1.0				
June 9, a. m	132	7.6	171	5.8	212	4.7	298	3.4								
9, p. m							179	5.6								
10, a. m			1,092	0.9			534	1.9								
10, a. m	102	9.8	139	7.2	157	6.4	242	4.1								
21, p. m			153	6.5	176	5.7	176	5.7								
26, a. m	112	8.9	176	5.7	242	4.1	300	3.3								
26, a. m							207	4.8								
July 7, a. m	239	4.2	200	5.0	241	4.1	251	4.0								
Sept. 13, a. m			231	4.3	205	4.9	201	5.0	203	4.3						
13, p. m	137	7.3			146	6.8	167	6.0								
16, a. m	187	5.3			314	3.2	181	5.5								
16, p. m			148	6.8	215	4.7										
21, p. m					218	4.6	204	4.9	185	5.4						
21, p. m	167	6.0	182	5.5	191	5.2										
30, p. m	131	7.6	146	6.8	165	6.1										
Oct. 3, p. m	135	7.4	187	5.3	753	1.3	554	1.8								
3, p. m	131	7.6	148	6.8	399	2.5										
9, p. m	129	7.8			147	6.8	162	6.2								

SUMMARY.

CLEAR.

Morning		6.9		5.8		3.9		3.4		3.9		3.9		4.5		4.6
Afternoon		8.1		7.2		6.6		5.4		4.9		4.7				6.2
Mean		7.5		6.6		5.0		4.1		4.3		4.1		4.5		5.1

CLOUDY.

Morning		7.6		4.4		4.7		3.2		2.3		3.2				4.2
Afternoon		6.8		6.1		4.9		6.0		5.0						5.6
Mean		7.1		5.2		4.8		4.0		2.9		3.2				4.5

COMBINED.

Morning		7.0		5.4		4.1		3.3		3.3		3.8		4.5		4.5
Afternoon		7.8		6.9		6.1		5.5		4.9		4.7				6.0
Mean		7.4		6.2		4.9		4.0		3.8		3.9		4.5		5.0

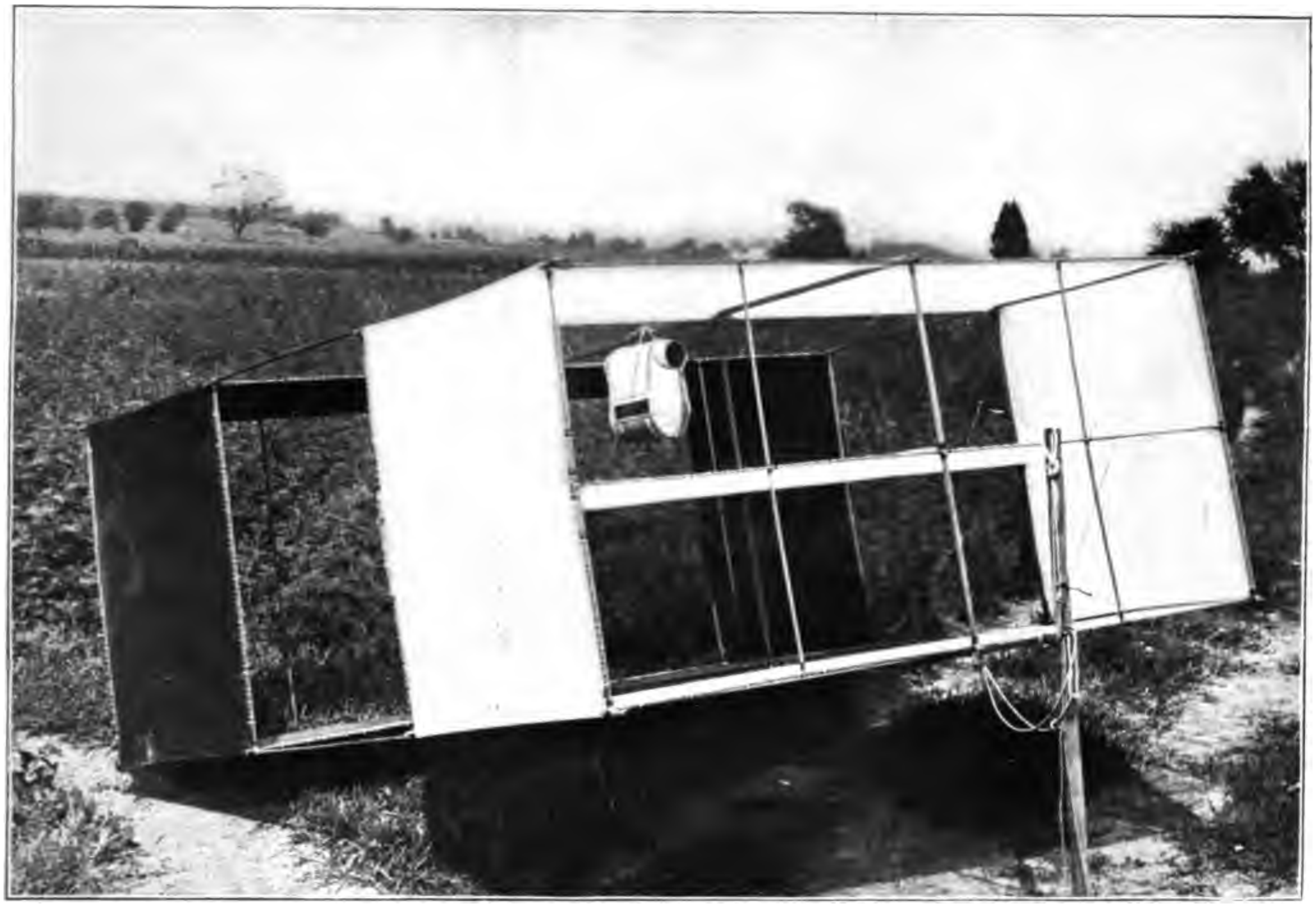


FIG. 1.—KITE WITH METEOROGRAPH IN PLACE.

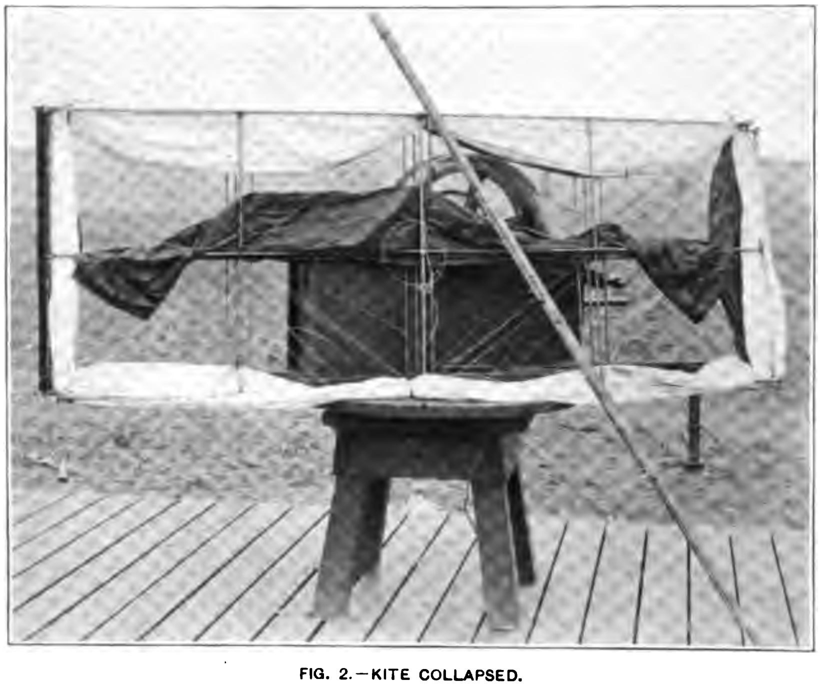


FIG. 2.—KITE COLLAPSED.

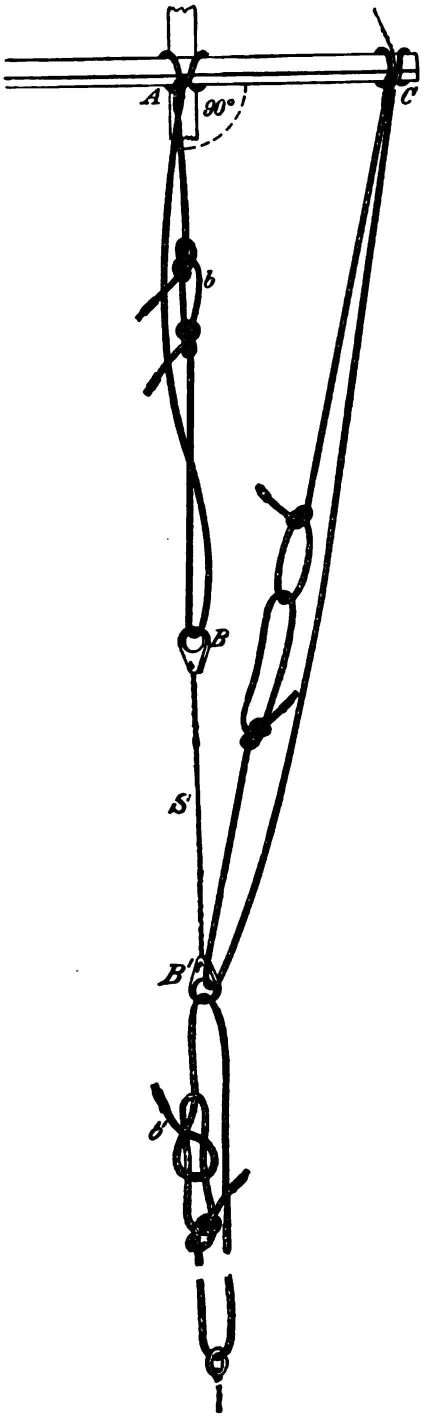
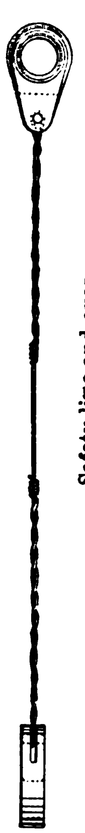


FIG. 3.—NORMAL BRIDLE.



—Safety line and eyes.

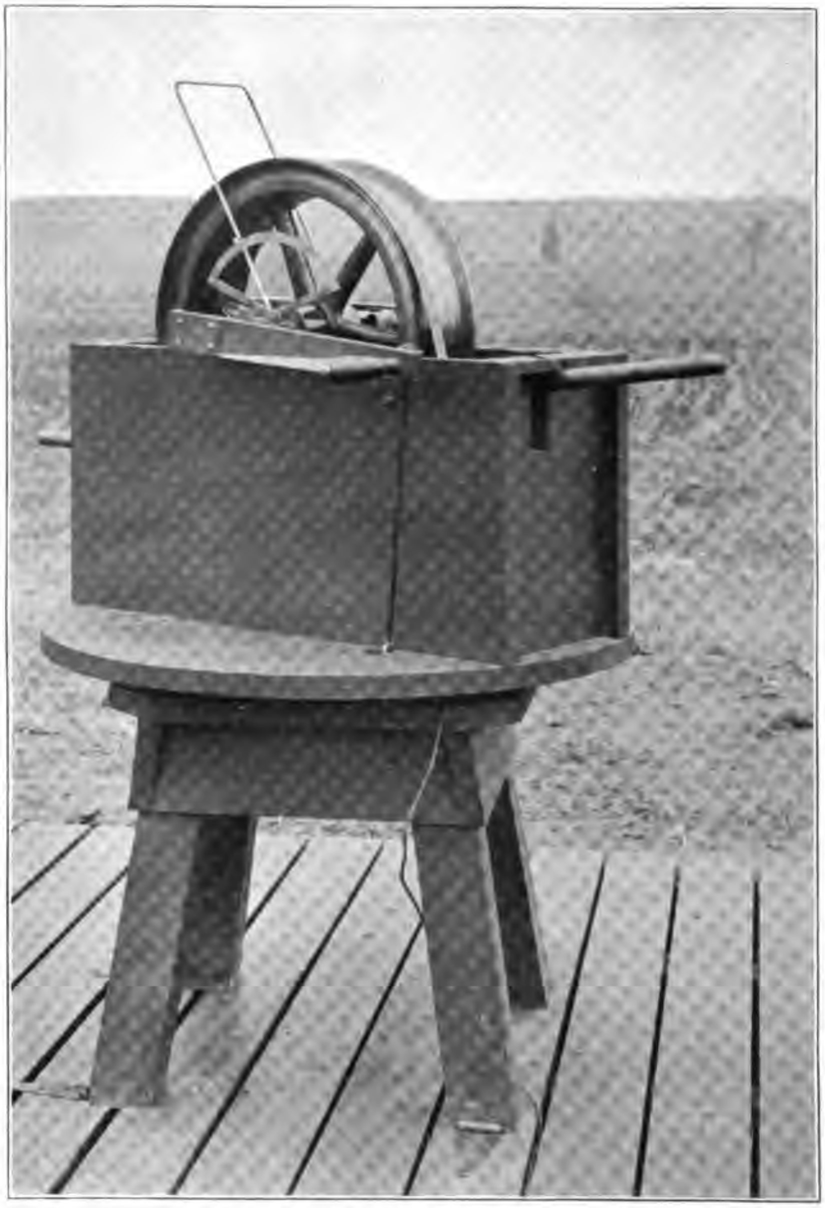


FIG. 4.—KITE REEL AND SUPPORT.

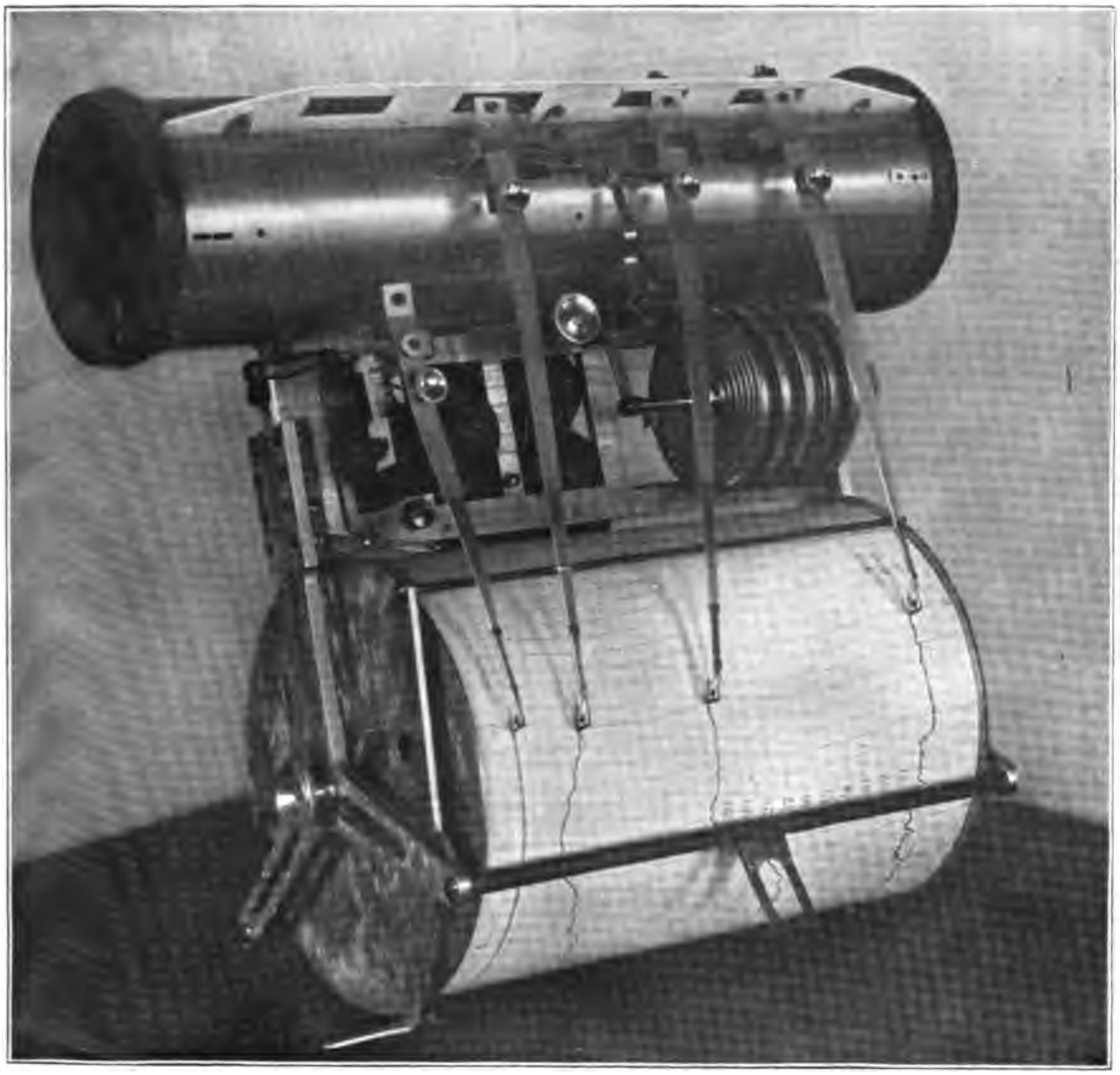


FIG. 5.—KITE METEOROGRAPH.

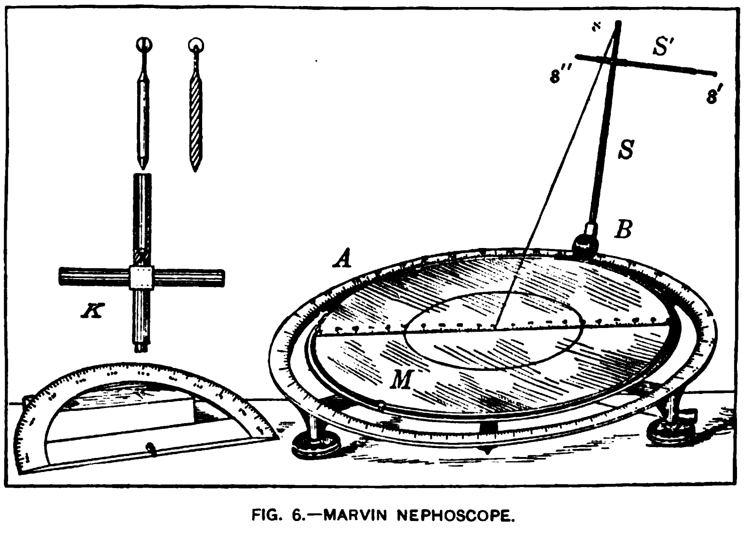


FIG. 6.—MARVIN NEPHOSCOPE.

PLATE I.

Morning.

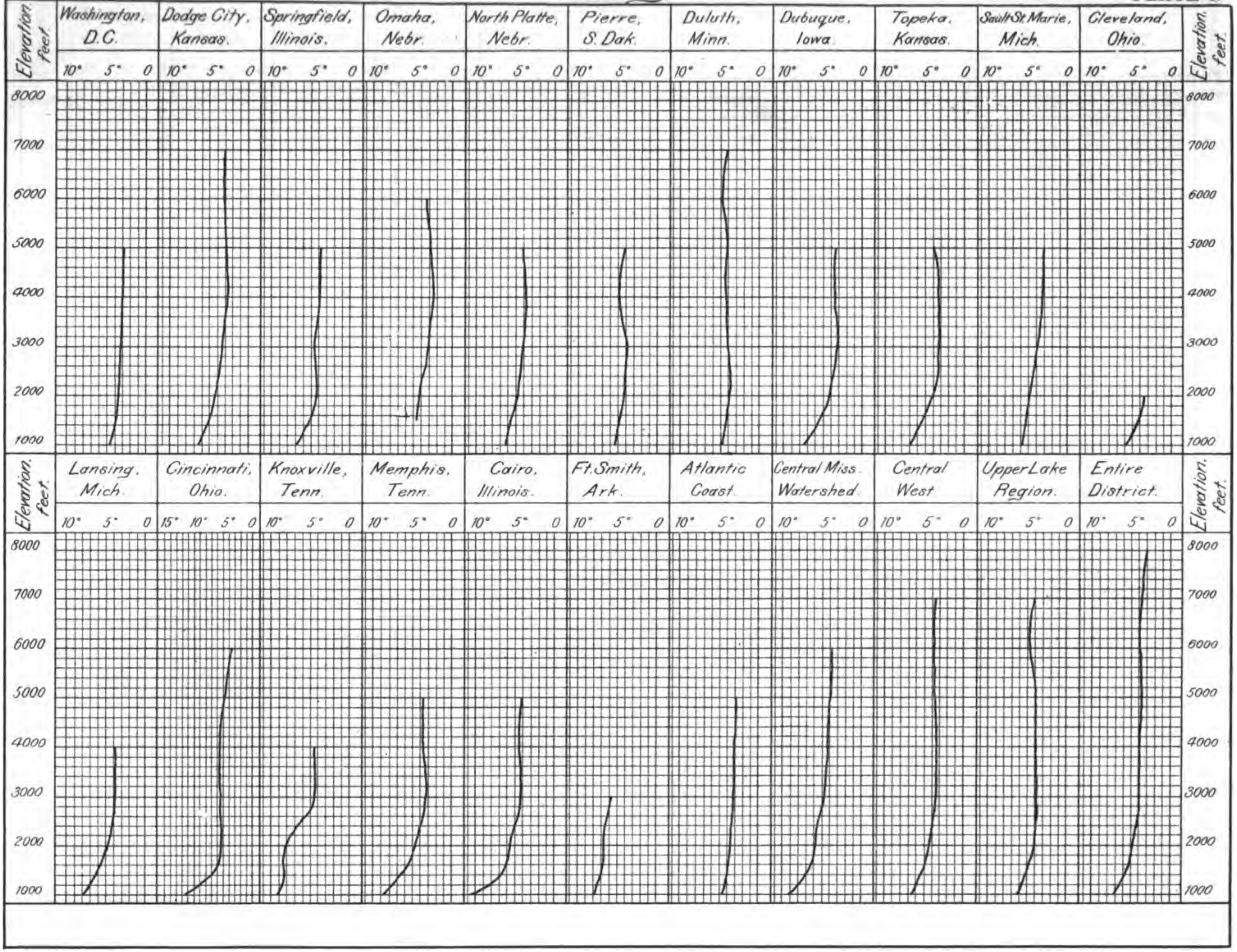


PLATE II.

Afternoon.

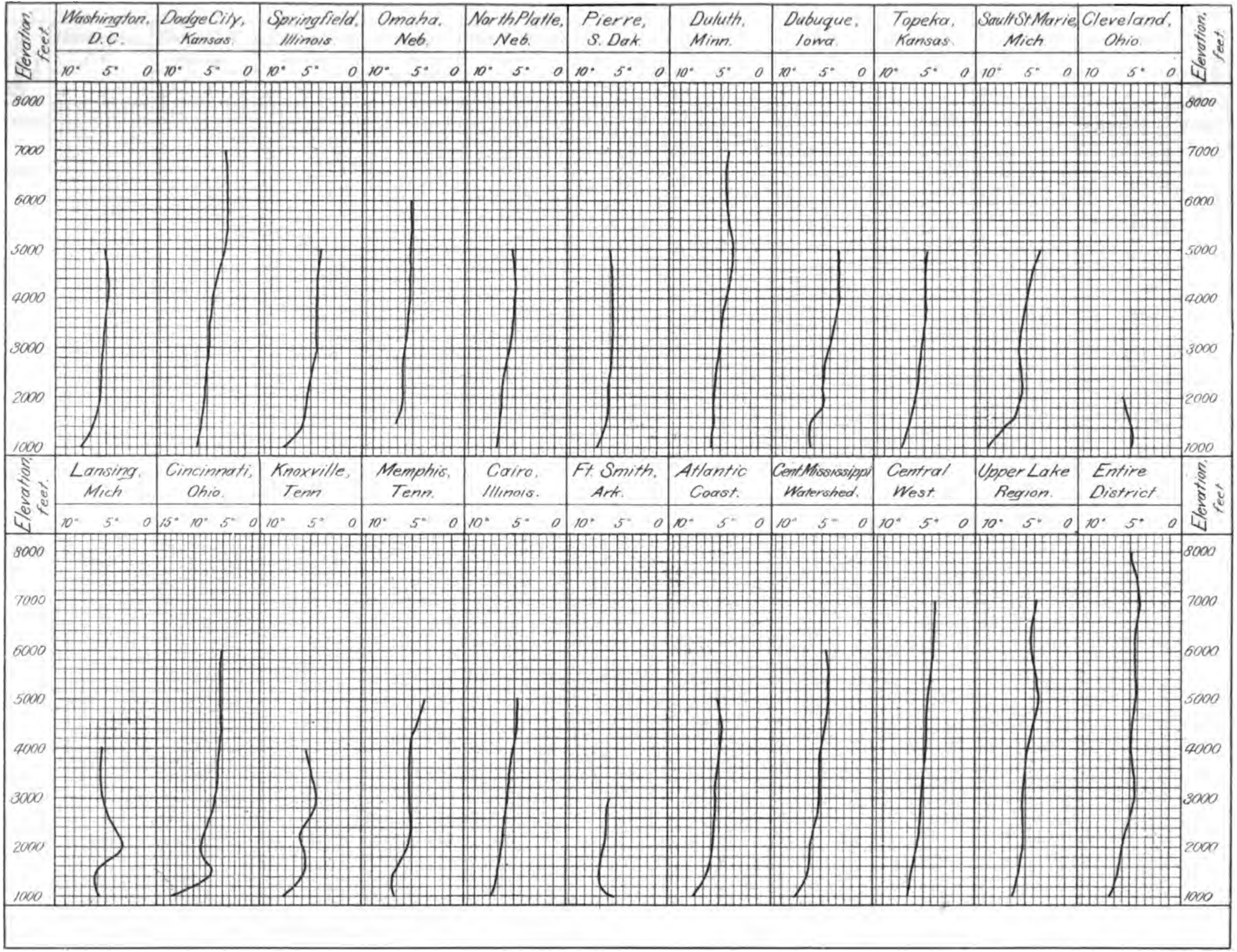
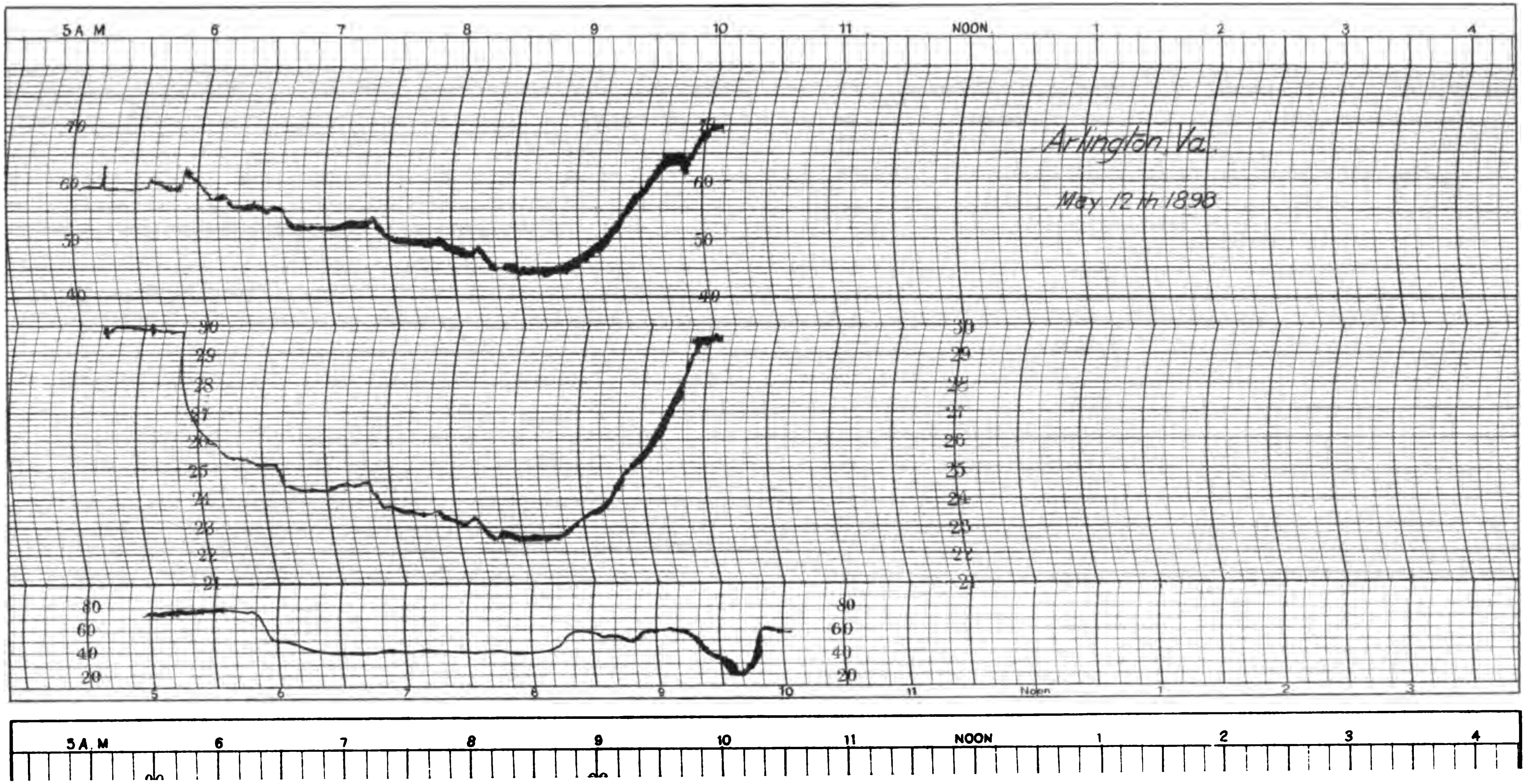


PLATE IV.

Kite Meteorograph Record Sheets.



BULLETIN G. W. B. No. 221.

U. S. DEPARTMENT OF AGRICULTURE.

WEATHER BUREAU.

ATMOSPHERIC RADIATION:

A RESEARCH

CONDUCTED AT THE ALLEGHENY OBSERVATORY AND AT PROVIDENCE, R. I.

SUBMITTED TO WILLIS L. MOORE, CHIEF U. S. WEATHER BUREAU,

BY

FRANK W. VERY.

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LETTER OF TRANSMITTAL.

UNITED STATES DEPARTMENT OF AGRICULTURE,
WEATHER BUREAU,
Washington, D. C., January 4, 1900.

Hon. JAMES WILSON,
Secretary of Agriculture.

SIR: I have the honor herewith to transmit for publication, as a bulletin of the Weather Bureau, a memoir by Prof. Frank W. Very on "Atmospheric Radiation."

This paper gives the results of a long research carried on by Professor Very during the past eight years. The expense of the apparatus was defrayed by Prof. James E. Keeler, Director of the Allegheny Observatory, from funds allotted for this purpose by the Hon. J. M. Rusk on the recommendation of my predecessor.

An examination of the manuscript will show that Professor Very has brought to bear upon the study of this important subject a wide range of knowledge and experimental skill acquired by his long service in connection with Prof. S. P. Langley in researches on radiation at the Allegheny Observatory. Professor Very has attacked a problem that has long been recognized as being of fundamental importance in climatology and general meteorology. He has apparently settled some questions that have heretofore been under discussion, but has also raised others for future investigators to discuss.

This memoir is, therefore, to be recognized as one step of progress in our knowledge of the subject of radiation and absorption of heat by the earth's atmosphere, and I take great pleasure in commending it to you.

Very respectfully, your obedient servant,

WILLIS L. MOORE,
Chief United States Weather Bureau.

Approved:
JAMES WILSON,
Secretary of Agriculture.

ATMOSPHERIC RADIATION.

By **Frank W. Very.**

PREFATORY NOTE.

This research was first suggested in a letter from Prof. Cleveland Abbe, of the United States Weather Bureau, to the writer, dated November 24, 1891, in the course of which he said:

> Absorption *may be* the absolute inverse of *radiation* for gases, but I don't like to assume this as to intensity, and so I beg to know whether you and Professor Keeler can not undertake the following problem: To determine the absolute radiation in calories from a unit mass of gas at given density and temperature and at ordinary temperatures, not when burning, nor when electrified, but when simply heated.
>
> Maurer has given the only determination that I know of, but this is only computed from meteorological observations of cooling at night, and his figures demand confirmation by direct experiment. He finds
>
> $\sigma =$ coefficient of radiation for air, or the amount of heat in calories that one *unit volume* of air
>
> [at the level of the station where $b = 29.5$ inches; temperature $= 40°$? Fahr.] loses by radiation in unit time (one hour) to a surrounding surface of air whose temperature is 1° lower $= 0.0000418$ gram calories per cubic centimeter per hour. And again from direct radiation observations, he finds 0.000039 calories.
>
> It ought to be possible to determine the quantity and quality of the heat radiated by a mass of warm gas. * * * The stream of gas should be varied as to its diameter, so as to determine the effect of depth from which radiation comes. The ascending flow of warm gas can be kept steady for any length of time or cut off at will. The black surface that serves as the basis for reference should be surrounded by a screen at 0°C., so that it can only receive and transmit or reflect the waves that belong thereto.

In regard to the direct measurement of gaseous radiations of nearly homogeneous quality at moderate temperatures, the following was written in reply (November 27, 1891):

> The problem which you suggest is an exceedingly difficult one. I should anticipate that the radiation from so small a mass of gas as that in a transverse jet would be almost immeasurable, unless at very high temperature. Possibly two long, diaphragmed tubes, surrounded by water jackets, and open at both ends, would answer for ordinary temperatures when interposed in alternation; *e. g.* let temperature of room be +20°C., one tube being surrounded by a freezing mixture at −20°C., and the other by warm water at +60°C. The temperature gradients in the open tubes would be similar and are also determinable.

In commenting on the above suggestion, Professor Abbe expressed the hope that temperatures as low as −90° C. might be attained, but added further the important remark that "the point to be determined experimentally is the law of radiation, transmission, and absorption as depending upon pressure or density of the air rather than as depending upon temperature."

By the advice and consent of Professor Keeler, Director of the Allegheny Observatory, preliminary experiments were commenced in March, 1892, with an apparatus similar to that outlined in the writer's letter of November 27, 1891; but as entire confidence could not be placed in any one method, and as the complete accomplishment of the work contemplated required measurements of atmospheric radiation at various pressures, a more elaborate apparatus was devised with which experiments were begun in 1894 and continued in the intervals between other occupations until the severing of my connection with the Observatory in 1895. The reduction of the observations begun at Allegheny was afterwards continued at Providence, R. I., and required the further consideration of a number of obscure and troublesome details for which I did not find time for several years, but it is hoped that the last of these difficulties has now been successfully met.

The problem has proved much more extensive than I imagined when I first undertook its solution. It is, besides, beset with difficulties. Some of the greatest masters of science have worked at it with only partial success, and with merely qualitative results. Professor Tyndall rightly emphasized the necessity of a long apprenticeship in the methods and manipulations appropriate to this study before one can be ready to appreciate the subtle sources of error to which this particular research is open. The investigator here is dealing with the invisible and the evanescent. In an optical apparatus, a little stray light immediately attracts attention, and we proceed to trace it to its source with our eyes open. In our study of feeble invisible radiations, on the other hand, we grope in the dark, and only succeed in eliminating the unwelcome extraneous rays after innumerable trials and errors.

The final apparatus for work at various pressures frequently gave trouble by springing leaks when heated; and the possibility of contamination of the air column by evaporation or combustion of organic substances prevented the employment of elevated temperatures. Moreover, it was especially desired that the temperatures should not greatly exceed those of the ordinary atmospheric range. Hence the radiations measured have been of small magnitude, requiring a sensitive measuring apparatus, and attention to many minute details inevitable in measurements of this character. I shall not trouble the reader with a recital of all the difficulties encountered; but, in order that the meaning and value of the results may be quite clear, it will be necessary to consider the theory of some parts of the apparatus carefully.

MEASURING INSTRUMENTS.

THE BOLOMETER.

The measurements of radiation have all been made with a bolometer constructed after Langley's earlier plans, in which the exposed face is composed of very thin strips of blackened platinum, arranged in two series, those in the rear occupying the positions of the apertures in the front series. The unexposed member is of nearly identical resistance and is divided into two parts, one on each side of the central member, which receives the radiation coming through the graduated apertures of the bolometer case. The electric current passes to and fro along the strips which are held separate and insulated by grooves in the disk of an ebonite holder, a disposition which is objectionable, as I shall show presently, but which does not prevent the instrument from being used for certain classes of relative measurements, where the accompanying conditions do not vary much.

The bolometer battery consisted of eight gravity cells arranged in one series, the current being reduced to its working strength by interposing resistance between the battery and the Wheatstone's bridge, of which the bolometer forms a part.

When a bolometer of two nearly equal arms is used, it is desirable, in order to secure the most sensitive combination, that the balancing arms of the Wheatstone's bridge should be of greater resistance than the bolometer arms, in case all of the resistances can not be made equal. Since in the bridge used by me, choice could be made between balancing resistances of 1, 10, or 100 ohms, the bolometer arms being a little over 31.5 ohms, at 20° C., or with connections about 32 ohms in all, the normal arrangement of the bridge is with balancing arms of 100 ohms. But on several occasions the bridge, being used for different purposes, was inadvertently left with balancing arms of only 10 ohms. It becomes necessary, therefore, to reduce these measures to normal sensitiveness of a 100 : 32 bridge.

According to theory, the current through the galvanometer is, by Kirchhoff's law:

$$C_5 = \frac{E\,(r_2 r_3 - r_1 r_4)}{D}$$

where

$$D = r_5 r_6 (r_1 + r_2 + r_3 + r_4) + r_5 (r_1 + r_3)(r_2 + r_4) + r_6 (r_1 + r_2)(r_3 + r_4) + r_1 r_3 (r_2 + r_4) + r_2 r_4 (r_1 + r_3).$$

In the normal arrangement (1), and the exceptional or insensitive arrangement (2), the currents in consecutive experiments were:

(1) Measured battery current = 0.026 ampere.
(2) " " " = 0.032 "

The extra resistance (R), plus that of the bridge, was:

(1) $R + \frac{1}{2}(r_1 + r_3) = 266$ ohms.
(2) $R + \frac{1}{2}(r'_1 + r_3) = 221$ "

Assuming the electromotive force of one gravity cell to be 1.1 volt, the total resistance of eight cells, plus an extra resistance of 200 ohms, plus the bridge, should have been:

(1) $$r_6 + R + \tfrac{1}{2}(r_1 + r_3) = \frac{8.8}{0.026} = 338.5 \text{ ohms.}$$

(2) $$r_6 + R + \tfrac{1}{2}(r'_1 + r_3) = \frac{8.8}{0.032} = 275.0 \text{ "}$$

whence the apparent resistance of the battery was:

(1) For eight cells, 72.5 ohms; for one cell, 9.2 ohms.
(2) " " " 54.0 " " " " 6.9 "

According to this, the diminution of the external resistance from 266 to 221, or by 17 per cent., increased the current by 23 per cent., the battery resistance at the same time diminishing by 25 per cent. It is possible that a portion of the change was in the potential of the battery, and both voltage and resistance may have been lower than the values given; but for the purposes of a test, the resistances may be taken as stated, and assuming further that the exposed arm of the bolometer has its resistance increased by radiation by 0.005 ohm, I proceed to calculate the current through the galvanometer in each of the two arrangements of the bridge. The resistances at 20°C. are those of the Elliott coils, graduated according to British Association units, of which 1 = 0.989 of the the accepted legal ohm.

(1) $r_1 = r_2 = 100,\quad r_3 = 32.005,\quad r_4 = 32,\quad r_5 = 20.5,\quad r_6 = 272.5.$*
(2) $r'_1 = r'_2 = 10,\quad r_3 = 32.005,\quad r_4 = 32,\quad r_5 = 20.5,\quad r'_6 = 254.$

$$D_{(1)} = (20.5 \times 272.5 \times 264.005) + (20.5 \times 132.005 \times 132) + (272.5 \times 200 \times 64.005) + (100 \times 32.005 \times 132) + (100 \times 32 \times 132.005) = 6\,165\,159.$$

$$D_{(2)} = (20.5 \times 254 \times 84.005) + (20.5 \times 42.005 \times 42) + (254 \times 20 \times 64.005) + (10 \times 32.005 \times 42) + (10 \times 32 \times 42.005) = 825\,609.$$

Computed ratio of galvanometer currents:

$$\frac{C_{5\,(1)}}{C_{5\,(2)}} = 1.339 +$$

The theory was tested by exposing the bolometer to radiation from blackened screens containing boiling water, and water at the temperature of the room (about 30° C.) with the following results:

(1) $r_1 = r_2 = 100$ ohms.

Temperature of screens.	Deflection
99°.1	366 div.
29°.4	364
——	367
Excess, 69°.7 C.	367
	364
	362
	365
	363
	363
	361
Mean deflection	=364.2

(2) $r'_1 = r'_2 = 10$ ohms.

Temperature of screens.	Deflection.
99°.1	232 div.
30°.2	232
——	232
Excess, 68°.9	235
	233
	231
	231
	230
	230
	230
Mean deflection	=231.6

---

* r_6 is supposed to include the extra resistance R.

Galvanometer deflection for 1° of temperature-excess:

(1) 5.225 div. (2) 3.361 div.

Ratio of observed galvanometer currents:

$$\frac{C_5\,(1)}{C_5\,(2)} = 1.555$$

To bring the computed value into agreement with the observed, a battery resistance of nearly 1,000 ohms would be required; but this is entirely inadmissible, since any bad connection would have reduced the current and the galvanometer deflection, both of which were such as to give customary values in the normal reduction. For constant battery current the ratio of galvanometer currents with the two arrangements should be:

$$\frac{C_5\,(1)}{C_5\,(2)} = 1.339 \times \frac{0.032}{0.026} = 1.648 \text{ (computed)}$$

$$\frac{C_5\,(1)}{C_5\,(2)} = 1.555 \times \frac{0.032}{0.026} = 1.913 \text{ (observed)}$$

Using the observed factor, observations with insensitive condition of the bridge are brought into fair agreement with normal measures, but the computed factor gives discordant results. There can be no doubt, therefore, of the substantial accuracy of the observed ratio. A study of these discrepancies has elucidated some obscure points in the theory of the bolometer, which I will indicate.

The sensitiveness of a bolometric apparatus is a complex of many factors. It depends upon the resistance of the bolometer, the material of its strips, and the rate at which the metal varies in resistance with changes of temperature, the absorbent quality of the surface for rays of various wave-lengths, the area exposed to radiation, the thickness of the strips, the resistance and form of the galvanometer coils, the strength of the magnets forming the needle, the ratio of their mass to the other parts of the needle, their dimensions and position in reference to the galvanometer coils, the astaticism and damping of the needle, the torsion of its suspending fiber, the strength of the external magnetic field, the arrangement of the Wheatstone's bridge, the strength of battery current employed, and the excess to which the bolometer strips are heated by the current. The last is a very important factor, and is probably responsible for the greater part of the discrepancy between incomplete theory and observation in the preceding example. The theory of the bolometer, in fact, can not be reduced to a simple case of Wheatstone's bridge, unless all of the factors, with the exception of the trifling change of resistance produced by the radiation to be measured, have remained constant.

Prof. Harry F. Reid, in his "Theory of the bolometer" (*Am. Journ. of Sci.*, ser. 3, vol. 35, p. 160, Feb., 1888), has given a formula for the bolometer with its whole surface blackened:

$$\delta = \frac{D\alpha H}{4}\,\frac{a}{\sqrt{2m}}\,\sqrt{i\lambda\beta\,(t_1 - t_0)}$$

in which δ is the galvanometer deflection, D the galvanometer constant, α the ratio of the resistance of the bolometer strips at the temperature $t_0 + 1°$ to their resistance at temperature t_0, H the intensity of normal radiation per unit of area expressed in thermal units, a the relative absorbent power of the bolometric surface exposed to radiation, m the loss of heat by combined radiation and convection (conduction being assumed negligible) in thermal units for the unit of time and unit surface of the strips, i the ratio of the resistance of the exposed part of the strips to the entire arm of the Wheatstone's bridge of which they form a part, λ the total length in series of the exposed part of the bolometer strips, β the width of an individual strip, and $t_1 - t_0$ the excess of temperature of the strips due to the battery current which enters as the square root of this quantity, the current being here stated in thermal units, and the galvanometer constant also having reference to these units. The formula also relates to the most efficient arrangement of the bridge resistances, but small variations from this ideal are of minor importance, the main point being that the bolometer arms shall have, as nearly as possible, equal resistances, and be inclosed in a common chamber which can be kept at a nearly constant temperature.

Professor Reid says (p. 165–166):

> Since the resistance of the strip does not enter the equation, it is of no importance so long as the four arms of the bridge and the galvanometer all have the same resistance; but this should not be so small as to decrease materially the value of i, or to make the galvanometer connections an appreciable fraction of the resistance in the galvanometer branch. λ and β only occur multiplied together and under the radical sign; other things being equal, δ varies as the square root of the exposable area of the strip. For a given area it does not matter, then, whether the strip be made of a single broad piece of platinum or of several narrow pieces arranged side by side and connected in series. This however, is subject to the limitations mentioned in regard to the resistance of the strip. The thickness of the strip does not occur in the expression above; we have supposed the strip flat and so thin that the edges are only a very small fraction of the surface and the heat lost by conduction negligible. As long as these are true the actual thickness of the strip is unimportant. $(t_1 - t_0)$ is the increase in the temperature of the strip above the case due to the current passing through it; for a particular bolometer it is proportional to the square of the current.

The equation is not of general applicability, and some of the assumptions made in deducing it are not warranted by facts of observation. Thus experiments which I have made, some of which will be described presently, prove that conduction of heat can not be neglected in platinum two or three microns thick, such as is used in bolometers. Again, the relation between the heat generated by the current and the temperature of the strip, deduced "according to Newton's law of cooling, which is sufficiently accurrate for the small change in temperature under consideration," in Professor Reid's estimation, is shown by observation to require a more complex expression, the loss of heat from thin strips being largely produced by convection, which is not nearly proportional to excess of temperature, even though this be small.

In the derivation of the above equation the galvanometer resistance has been assumed equal to that of one arm of the bolometer; but, as shown by Schwendler (*Phil. Mag.* (4), vol. 33, p. 29, 1867), the neglect of the space occupied by insulating material has led to an error in this customary allowance, and Mr. F. A. Laws (*Phys. Rev.*, vol. 5, p. 300, 1897) shows by trials of various windings that in a properly wound galvanometer the galvanometer resistance should be more nearly one-half that of one of the bridge arms if the maximum deflection is required. However, we are not concerned so much with those factors which influence the galvanometer constant as with those which enter into the variable bolometric effect.

The excess of temperature $(t_1 - t_0)$, which in a given bolometer depends mainly on the battery current, varies with the square of the current and inversely as the section of the strip. It is therefore a function of β, the breadth, and θ, the thickness of the strip. But if $\delta \propto \sqrt{\lambda \beta (t_1 - t_0)}$, the substitution of the relation, $t_1 - t_0 \propto \frac{1}{\beta}$, in this variable relation gives:

$$\delta \propto \sqrt{\lambda}$$

and other things being equal. that bolometer which is subdivided into the largest number of strips, or has the largest ratio between λ and β, should give the greatest galvanometer deflection. Possibly this might actually be the case in a vacuum, but in air more than one cause interferes with its realization. To keep the thin metal strips from undesired electric communication an ebonite holder with interlocking grooves has been used in the instrument belonging to my outfit. The heat retained by the nonconducting holder and by impeded convection very nearly neutralizes any gain that might result from the subdivision. But the theory does not yield readily to pure mathematics, and I proceed to experiments which throw some light on the activities in play in a working bolometer.

The measures in the following table were made several years ago by Professor Reid and myself, and were laid aside as hopelessly discrepant; but with further experience I am able to explain the discordances, and to show that they contain the key to a fuller theory of the actual instrument. The experiments were made on a nearly constant source of radiation with a single bolometer, varying the battery current and the aperture in order to get some knowledge of the connection between $\lambda \times \beta$ and $t_1 - t_0$. The quantity $(2v)$ is the battery current, given first as originally read in divisions of the arbitrary scale of the battery galvanometer, and afterwards in amperes as corrected by the calibration of the scale. The constant of this galvanometer is 1 div. = 0.000 33 amp. near 100 div. T is the excess of temperature of the radiator. The other symbols are as already defined. The seventh column gives values reduced to uniform battery current and the eighth to full aperture.

TABLE 1.

1 i	2 $\lambda\beta$	3 T	4 $2v$		5 δ	6 $\frac{\delta}{T}$	7 $\frac{.033\,\delta}{2vT}$	8 For aperture of i_1
	sq. mm.	°C.	*div.*	*amp.*	*div.*			
i_1=0.60	8.64	81.0	60	=0.0214	72.5	0.895	1.383	1.340
i_1=0.60	8.64	81.7	82	=0.0279	85.2	1.043	1.234	
i_1=0.60	8.64	83.7	166	=0.0480	157.9	1.886	1.301	
i_1=0.60	8.64	82.6	180	=0.0508	176.4	2.138	1.388	
i_1=0.60	8.64	81.5	196	=0.0537	185.4	2.275	1.396	
i_2=0.38	5.40	81.1	115.5	=0.0366	81.2	1.001	0.902	1.425
i_2=0.38	5.40	80.4	126	=0.0391	92.2	1.147	0.972	1.536
i_3=0.25	3.60	79.9	160	=0.0467	77.7	0.972	0.685	1.644
i_3=0.25	3.60	79.4	173	=0.0493	98.4	1.239	0.832	1.997

The exposed parts of the bolometer strips constitute 62.4 per cent. of the whole, or allowing for the resistance of the connections, 60 per cent. of the total resistance of the bolometeric arm of the Wheatstone's bridge is exposed in condition i_1. The mean currents giving unit deflection per degree of temperature-excess are given in the second column of the next table.

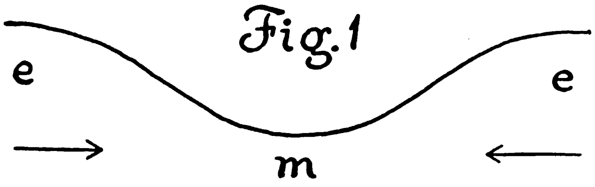
TABLE 2.

Exposed part. i	Battery currents. $2v$	Equally efficient currents $= 2v \times i$
	Ampere.	*Ampere.*
i_1=0.60	0.0252	0.01512
i_2=0.38	0.0353	0.01341
i_3=0.25	0.0434	0.01085

When the aperture of the inner bolometer chamber is reduced, a larger battery current is required to give a constant galvanometer deflection, but a current which is smaller than the inverse proportion of the aperture. The smaller exposed area is therefore more efficient for the unit of battery current, and the reason of this seems to be because the central part of the strips, heated by radiation, are adjoined, in the case of the smaller aperture, by larger portions of free strips at a slightly lower temperature, into which the heat can pass by conduction to be dissipated through a larger surface, but at a lower excess of temperature. One might hesitate to predict whether the larger surface or the lower excess would have the predominating influence, although in general two units of surface radiate less than one unit at twice the excess of the two, and the experiment decides in favor of this view, for the losses are less when the heat is distributed to a relatively wider area, so that a smaller current is then needed to produce a given deflection.

Let a_1 be the area of the fully exposed bolometer strips, a_2, the area of the central part when the aperture of the bolometer chamber is reduced, and Ha_1, Ha_2, the heat received from radiation in the two conditions. Owing to the slight thermal conductivity of the ebonite holder, the heat developed by the current in the covered parts of the bolometer raises the temperature of the ends of the strips excessively, the heat from the covered ends being partly dissipated by conduction to the freely exposed parts, where it passes off by radiation and convection. The distribution of temperature in the shielded strip is therefore something like the curve in fig. 1, the ends (e) being at a higher temperature than the middle (m), and the flow of heat being in the direction of the arrows.

Fig. 1



If c'' is a current larger than c', the excess of temperature of the strips at the ends under these respective currents will be:

$$(t''_1 - t''_o)_e > (t'_1 - t'_o)_e \left(\frac{c''}{c'}\right)^2 \tag{1}$$

while unless conduction more than compensates for the relatively greater loss by radiation and convection at the higher excess, the corresponding quantity in the middle of the strips will be:

$$(t''_1 - t''_o)_m < (t'_1 - t'_o)_m \left(\frac{c''}{c'}\right)^2 \tag{2}$$

and in any case

$$(t_1 - t_o)_e > (t_1 - t_o)_m \,, \tag{3}$$

the subscript e and m denoting end and middle positions.

During exposure of the central part of a strip to radiation, conduction from the sides in that part must be diminished or reversed. Since the temperature-excess imparted by a given quantity of heat is smaller when the initial temperature is greater, $t_2 - t_1$ must be less at the ends than at the center of the strip, and less at the middle for the greater current; also the mean $t_2 - t_1$, or the mean excess of temperature produced by radiation received, must be less for the fully exposed than for the centrally exposed strip; consequently, λ_1 and λ_2 being lengths of the exposed part of the strips for full and for partial exposure, and the temperature varying symmetrically in the two halves of a strip,

$$\frac{(t_2 - t_1)_e + (t_2 - t_1)_m}{2} < (t_2 - t_1)_m \,. \tag{4}$$

For the currents c' and c'' the deflections are approximately:

$$\delta'_1 \propto \frac{\sum_o^{\frac{1}{2}\lambda_1} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_1} \times (\alpha\, a_1\, c') \tag{5}$$

($\varDelta\lambda$ being a small element of length, α the coefficient of change of resistance with temperature).

$$\delta'_2 \propto \frac{\sum_o^{\frac{1}{2}\lambda_2} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_2} \times (\alpha\, a_2\, c') \tag{6}$$

$$\delta''_1 \propto \frac{\sum_o^{\frac{1}{2}\lambda_1} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_1} \times (\alpha\, a_1\, c'') \tag{7}$$

$$\delta''_2 \propto \frac{\sum_o^{\frac{1}{2}\lambda_2} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_2} \times (\alpha\, a_2\, c'') \tag{8}$$

in which

$$\frac{\sum_o^{\frac{1}{2}\lambda_1} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_1} < \frac{\sum_o^{\frac{1}{2}\lambda_2} (t_2 - t_1)(\varDelta\lambda)}{\frac{1}{2}\lambda_2} \,.$$

Observation shows that

$$\delta'_1 \div a_1\, c' < \delta'_2 \div a_2\, c' \tag{9}$$

$$\delta''_1 \div a_1\, c'' < \delta''_2 \div a_2\, c'' \tag{10}$$

$$\delta'_1 \div a_1\, c' > \delta''_1 \div a_1\, c'' \tag{11}$$

$$\delta'_2 \div a_2\, c' < \delta''_2 \div a_2\, c'' \tag{12}$$

Hence, within specified limits,

$$\frac{\delta''_1}{a_1\, c''} < \frac{\delta'_1}{a_1\, c'} < \frac{\delta'_2}{a_2\, c'} < \frac{\delta''_2}{a_2\, c''} \tag{13}$$

Inequality (11) is a consequence of the unequal distribution of the temperature-excess developed by the battery current in the strips, and the law of increase of this excess at the preponderant ends, given by (1). Inequality (12), dealing with a part of the strips where temperature is fairly equable, is a consequence, as will be shown presently, of the great influence of convection in cooling, and the rapid rate at which convection increases with the temperature-excess in masses of matter of the form and temperature considered here. Inequality (13) expresses the fact, which has been demonstrated in the experiment already given, that bolometers of reduced aperture are relatively more efficient.

Bolometers used with full aperture, if of the same general construction, are as a rule more efficient per unit of area when the number of strips and the total area are smaller.

Determinations of the battery current required to produce a nearly constant deflection on an approximately constant source of radiation with three different bolometers, constructed with various arrangements of strips, but all having grooved ebonite holders, gave me the results in the next table.

TABLE 3.

(Deflections similar.)

Number of strips in each arm	n	1	5	23
Length of strips exposed	λ	8.5 mm.	48.0 mm.	184.0 mm.
Resistance of bolometer	R	9.2 ohm.	14.7 ohm.	82.1 ohm.
Fraction of resistance exposed	i	0.38	0.60	0.63
Area exposed	$\lambda\beta$	1.62 sq. mm.	8.64 sq. mm.	42.3 sq. mm.
Section of strips	$\beta\theta$	0.000209 sq. mm.	0.000504 sq. mm.	0.000322 sq. mm.
Thickness of strips	θ	0.0011 mm.	0.0014 mm.	0.0028 mm.
Battery current ($2v$) giving uniform deflection		150.5 div. =0.0447 amp.	60.0 div. =0.0214 amp.	13.0 div. =0.0055 amp.
Deflection (mean of 10 observations)	δ	73.4 div.	72.6 div.	75.8 div.
Probable error of 1 observation		±0.63 per cent.	±0.42 per cent.	±0.28 per cent.
Excess of temperature of radiant source	T	82° C.	80° C.	78° C.
Deflection per degree	$\frac{\delta}{T}$	0.895 div.	0.908 div.	0.972 div.
Heat developed by battery-current, computed as proportional to $(2v)^2 R$		7.41	2.71	1.00
Deflection per degree per sq. mm. exposed area		0.552 div.	0.105 div.	0.023 div.
Deflection per degree per mm. of λ		0.1053 div.	0.0189 div.	0.0053 div.
Ratio of efficiency per mm. of λ		19.9	3.6	1.0
Ratio of efficiency per sq. mm. of $\lambda\beta$		24.0	4.6	1.0
Ditto, computed for constant current on erroneous assumption $\delta \propto 2v$		2.934	1.176	1.000

In the next table, further measures, made with the same bolometers by Professor Reid and myself, give a comparison of deflections on a nearly constant source of radiation with approximately constant battery current.

TABLE 4.

(Currents similar.)

Number of strips in each arm	n	1	5	23
Length of strips exposed	λ	8.5 mm.	48.0 mm.	184.0 mm.
Battery current	$2v$	168.0 div.	166.0 div.	157.5 div.
Deflection (mean of 7, 16 and 10 observations)		91.0 div.	157.9 div.	327.2 div.
Probable error of one observation		±0.85 per cent.	±0.44 per cent.	±0.33 per cent.
Excess of temperature of radiant source	T	75°.5 C.	83°.7 C.	78°.4 C.
Deflection per degree		1.205 div.	1.886 div.	4.173 div.
Heat developed by battery current, computed as proportional to $(2v)^2 R$		1.00	1.56	7.85
Deflection per degree per sq. mm. exposed area		0.744 div.	0.218 div.	0.099 div.
Deflection per degree per mm. of λ		0.1418 div.	0.0393 div.	0.0227 div.
Ratio of efficiency per mm. of λ		6.25	1.73	1.00
Ratio of efficiency per sq. mm. of $\lambda\beta$		7.52	2.20	1.00

The relative efficiency of unit area of the bolometer is diminished by the use of an excessive battery current, which evolves so much heat that it can not be dispersed rapidly enough in the rather limited chamber of the bolometer case to prevent undue increase of the primitive excess (t_1-t_0), thereby diminishing the increment (t_2-t_1), due to radiation. A comparison of the relative efficiencies, given in the last lines of Tables 3 and 4, and of the heat developed by the battery current, shows that whereas, with equal currents, the single-strip bolometer is actually about seven and one-half times as efficient as the 23-strip instrument, the heat being nearly eight times as great in the latter, reduction of observations made with unequal currents makes the computed efficiency of the single-strip instrument for equal currents only about three times that of the other, when the heat in the single strip is over seven times as great as in the 23-strip bolometer.

On the other hand, the probable errors of single observations maintain much the same relation when the order of excessive heating by the current is reversed. The deflections with uniform current are by no means inversely proportional to the exposed areas, as the last line of Table 4 shows, the deflection per square millimeter being much greater for the smaller instruments; but this can not be due entirely, or mainly, to diminished values of t_1-t_0 for the smaller, as compared with the larger instruments, for otherwise there should be a reversal of efficiency when the order of excessive heating is reversed, and at least some change in the relation between probable errors.

One other factor remains to be considered—the form of the bolometer. It is evident that a large part of the heat in the strips is removed by convection, and that convection is much impeded in the double-layer, alternate-aperture, gridiron-pattern, or multiple-strip bolometer, while in a single-strip instrument, or one of few and narrow strips, the adherent sheaths of heated air slip from the metal much more readily. The primitive excess of temperature is much less, therefore, in the simpler bolometer, and the excess imparted by radiation is greater. It is difficult to give a mathematical expression for this factor, but the experiments described in the foregoing pages indicate its importance. The removal of hot air by convection is not a perfectly continuous process, but an alternation of instants of quiescence, during which heat accumulates, and the establishment of miniature whirlwinds, by which the hot air is swept away. The irregularities thus produced account for the larger probable errors in those instruments where convection is least impeded. If the battery current is reduced until the probable error for one observation is the same in every case, there is little difference between the deflections from single-strip and multiple-strip bolometers of the same metal.

In the next experiment the mean temperature of excess of the bolometer strips (T), corresponding to (t_1-t_0) in Professor Reid's formula, was calculated, by Callendar's formula* for platinum resistance, from the measured resistances, when different currents (C) were used.

TABLE 5.

Current C.	Temperature excess (T).	$\frac{C^2}{C_2^2}$	$\frac{T}{T_2}$
Ampere.	C. °		
$C_1=0.0011$	$T_1=0.0$	....	....
$C_2=0.0119$	$T_2=0.6$	1.000	1.000
$C_3=0.0279$	$T_3=3.6$	5.497	6.000
$C_4=0.0427$	$T_4=10.4$	12.875	17.333
$C_5=0.0505$	$T_5=15.8$	18.008	26.333

The last two columns show that the mean temperature-excess increases more rapidly than the square of the current, indicating that the confinement of parts of the circuit and the impeding of convection are responsible for the departure.

Returning now to the experiments described on page 7, *et seq.*, the following temperature-excesses are indicated for the bolometer, by the measures in Table 5:

(1) Battery current, $C_1 = 0.026$ amp., temperature-excess, $T_1 = 3^{\circ}.0$ C.
(2) " " $C_2 = 0.032$ amp., " " $T_2 = 5^{\circ}.0$ C.

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* $R=1+0.00346\ T$. (See *La Lumière Electrique*, January 8, 1887, p. 78.) Measurements of the resistance of the same bolometer at constant temperatures, in summer and winter, agreed well with this law.

The heat generated by the current in the second case is to that in the first as $(0.032)^2 : (0.026)^2 = 1.515$.

The temperatures maintained are in the ratio: $5.0 : 3.0 = 1.67$.

The ratio for the central part of the strips where the radiation is received, will be smaller than this, as has been pointed out before (inequality 3); but this will not affect the argument, since the diminution of the temperature-ratio is accompanied by an increase of the factor for convection.

A comparison of the loss of heat from thin strips and from the spherical bulb of a small thermometer is instructive. Experiment has shown that the thermometer at corresponding temperature-excesses

$T_1 = 3^\circ.0$, cools $0^\circ.71$ per minute.
$T_2 = 5^\circ.0$, cools $1^\circ.24$ per minute.

The dimensions and water-equivalent of the thermometer bulb were such that these represent, respectively,

0.001032 small calories per sq. cm. per sec.
and 0.001802 " " " " " "

The platinum in one arm of the bolometer had a water-equivalent of about 0.00002 gram, and the heat developed in it by the current was:

(1) $$(\tfrac{1}{2} \times 0.026 \times 10^{-1})^2 \times \frac{32 \times 10^9}{4.2 \times 10^7} = 0.00129 \text{ calory per sec.}$$

(2) $$(\tfrac{1}{2} \times 0.032 \times 10^{-1})^2 \times \frac{32 \times 10^9}{4.2 \times 10^7} = 0.00195 \text{ " " "}$$

The cooling in the two cases must have been:

(1) $$\frac{0.00129}{0.00002} = 64^\circ.5 \text{ per sec.}$$

(2) $$\frac{0.00195}{0.00002} = 97^\circ.5 \text{ " "}$$

which, as the temperature-excesses are so much smaller, shows that the strips lose the greater part of their heat in a small fraction of a second. The total area (both sides) of the platinum being about 0.6 sq. cm., the losses are

(1) 0.00215 small calory per sq. cm. per sec.
(2) 0.00325 " " " " " "

taking place partly by radiation through the limited aperture of the ebonite frame holding the strips, and partly by convection from a surface whose ratio to the volume is about 3,000 times as great as that of the thermometer bulb. In the thermometer I have determined the loss by convection as a percentage of the total loss, getting the values in the following table:

TABLE 6.

T.	Convection.	T.	Convection.
°	*Per cent.*	°	*Per cent.*
1	6.5	9	24.8
2	11.0	10	25.8
3	14.5	11	26.7
4	17.0	12	27.4
5	19.2	13	28.0
6	21.0	14	28.6
7	22.5	15	29.2
8	23.7	16	29.8

By the measurements of Dr. J. T. Bottomley* on the emissivity of wires in vacuum and in air, it is evident that, in a wire 0.2 mm. thick at temperature-excesses of 150° and 200° C., convection is about fifty times as great as radiation, which is probably due to the readiness with which successive sheaths of heated air slip off from such a surface. Suppose the thickness of the air sheath to be ten times that of the wire, air to the depth of 2 mm. being heated by molecular interchange. The adhesion between the two must be very slight, but increases with the diameter of the wire.

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* *Phil. Trans. Royal Soc. London*, 1887 (A), p. 429.

I have been unable to determine the convective ratio for a bolometer, but it is probably safe to assume that it is intermediate between that of a wire of diameter the same as the width of a single bolometer strip (about 0.2 mm.), and a thermometer bulb. Simply as an illustration, we may suppose the convection ratio is seven times as great as for a bulb. For small excesses, the radiation may be taken proportional to the rise of temperature, and increasing the convection ratios in the preceding table in the proportion 7: 1, we have:

(1) $T_1 = 3^\circ.0$ Radiation + convection $= 1.00 + (7 \times .145 \times 1.00) = 2.015$.
(2) $T_2 = 5^\circ.0$ Radiation + convection $= 1.67 + (7 \times .192 \times 1.67) = 3.914$.

Ratio of total losses $= \frac{3.914}{2.015} = 1.942$.

In (2) the temperature being 67 per cent. greater than in (1), the losses are 16.3 per cent. greater than a simple proportion to the losses at the lower temperature, and the rise of temperature produced by a constant radiation is correspondingly less effective in changing the resistance of the bolometer, which may be expressed in terms of galvanometer current by multiplying the computed relative efficiency of the two arrangements of the bridge (p. 7) by 1.163, giving the corrected ratio

$$\frac{C_5\,(1)}{C_5\,(2)} = 1.339 \times 1.163 = 1.557,$$

which is not far from the observed ratio, 1.555, now finally adopted. For equal currents this ratio becomes 1.91, and by this factor all deflections taken with the insensitive arrangement of the bridge have been multiplied.

The value assumed for the convection ratio, according to this test, is slightly too large; but in any case it can not be quite correct, since no allowance has been made for thermal conduction in the thin strips. I am not able at present to give an estimate of this factor, but the following experiment makes its existence probable in metal as thin, or very nearly as thin, as that used for bolometers.

I first heated the front surface of a sheet of platinum, 4 μ thick and blackened on both sides, by radiation from a lamp, and measured the increment of radiation from the rear surface of the platinum by means of a bolometer which was, of course, completely shielded from the direct rays of the lamp. Nearly two minutes were consumed in reaching a maximum deflection. Fearing some secondary effect, due to the gradual heating of the perforated screens which limited the bundle of rays falling on the platinum, the experiment was modified as follows: The sheet of blackened platinum covered the aperture of the bolometer case and was in turn protected by a double cardboard screen with 2-cm. circular apertures centrally situated. A sunbeam of 5.7 cm. circular section, kept fixed by a heliostat, fell upon a concave mirror of 150 cm. focus, and the solar image was formed upon the center of the platinum foil. As before, the radiation from the rear surface of a sheet of platinum, receiving heat from the front by direct radiation on a very small part of its area, was to be measured. The sky was quite clear—the time from 11 to 12 a. m. All exposures were made by withdrawing a distant screen placed in the path of the sunbeam. The results contained in the following table show that much the larger part of the heat, being of course that of the small area embraced in the solar image, is obtained within the first ten seconds. The subsequent progressively diminishing increments can not be attributed to any heating of the bolometer case, since the insertion of a neutral screen behind the platinum made very little change in the deflection.

TABLE 7.

PLATINUM HEATING IN SUNSHINE.

0^{s}	10^{s}	20^{s}	30^{s}	40^{s}	50^{s}	60^{s}	70^{s}	80^{s}	90^{s}	100^{s}	110^{s}	120^{s}
0	183	193	203	208	213	215	216.5	217.7	217.5	219.0	219.5	220
0	193	204	215	223	228	231	233	234.7	236.3	239.1	238.9	239.1
0	187.4	196.8	205.2	212.6	216	220.6	221.8	223.5	225.4	225.1	224.4	225.6
Mean.	187.8	197.9	207.7	214.5	219.0	222.2	223.8	225.3	226.4	227.7	227.6	228.2
PLATINUM SHADED—COOLING.												
220	49	40	28	19.6	14.4	11.4	8.2	6.0	3.9	2.4	0.8	0
239.1	53	42	29	21	15	11.2	8.3	5.3	3.9	2.2	1.1	0
225.6	49.8	40.7	27.1	18.5	13.1	10.3	7.7	5.3	3.5	1.9	0.4	0
Mean.	50.6	40.9	28.0	19.7	14.2	11.0	8.1	5.5	3.8	2.2	0.8	0

Two minutes are consumed in attaining the maximum radiation, and the same in cooling. The whole of this retardation is not to be attributed to the slowness of conduction in the thin metal. A portion of the effect is due to the time required to establish a heat gradient in the air near the heated strip. The temperature acquired by the thin, blackened platinum in full normal sunshine is such as could be developed by the sun's rays in less than one-tenth of a second if all were absorbed. The same radiation is capable of heating an air layer around the platinum 4.5 mm. deep to the same temperature as the platinum in the same time, and there must be perpetual transfer of heat from the metal to some such layer of air in a bolometer exposed to full sunshine, since more heat is lost by convection than by radiation. How much of the heat in the experiment just described has been transferred from the focus to surrounding parts by conduction, and how much to parts above the focus by convection, can perhaps be determined in a repetition by mapping the distribution of heat in the foil, using a bolometer case of very small angular aperture.

It is evident from the foregoing studies that the thin metal strips of a bolometer had best be supported by stout metal arms at a distance from all insulating or obstructing partitions. Such an instrument has not been used in the present measures, but it is hoped that by keeping the conditions nearly the same, the results may still be capable of statement in terms of absolute measurement.

The actual bolometer used exposes a surface of 19.0 sq. mm., divided into fifteen strips, the total exposed strip-length being

$$\lambda = 15 \times 5.1 = 76.5 \text{ mm.}$$

The methods used in standardizing the instrument will be described under the head of "Screens."

THE GALVANOMETER.

The astatic reflecting galvanometer has a resistance of 20.5 ohms at 20° C. Its chief peculiarity is the needle, which is provided with hollow, cylindrical magnets of very hard steel, arranged in four groups of five each, on opposite sides of a straight, supporting, hollow glass fiber. Each group consists of one magnet 9.5 mm. long, two magnets, each 8.5 mm. long, and two of 6.0 mm. length, arranged symmetrically on pieces of mica, the cylinders being fastened by shellac and kept from contact with each other by minute bits of paper. The magnets are all of one diameter, 1.3 mm., and the weights of the various parts of the needle are as follows:

	mgs.
Twenty hollow cylindrical magnets	219.2
Concave mirror of platinized glass	63.0
Glass fiber (139 mm. long)	32.1
Copper suspension ring	2.0
Mica, paper, and shellac	17.3

In order to balance the mirror, attached to the west face of the upper system, and make the supporting glass fiber hang centrally in its well, a platinum vane, pointing east, was attached at the lower end of the glass fiber, bringing up the total weight of the needle to a little over 350 milligrams.

The rigidity of the needle is sufficient to resist the very slight strain experienced during an ordinary free deflection, but accidental maladjustment has sometimes to be corrected, and the method used in astaticizing may be of interest to those who work with similar instruments.

In a system as delicately constructed as this is, a slight knock or pressure is liable to disturb the parallelism of the planes of the upper and lower systems. Hence, if the upper and stronger system, indicated by the full line (*NS*) in fig. 2, has its plane displaced, so that its north-seeking poles lie on the east side of a vertical plane through the lower system (*N′S′*), there is a resultant magnetism at right angles to the mean plane of the system, and with its north-seeking poles on the east side of that plane. This resultant, combined with the original residual of the partially astatic system, turns the normal to the mirror (*P*) to the south of the west point. Some care is necessary, therefore, to secure an approach to astaticism and at the same time to keep the mean plane of the system in the magnetic meridian. The following mode of astaticizing has been found advantageous, and, with care, can be applied without dismounting the delicately suspended needle.

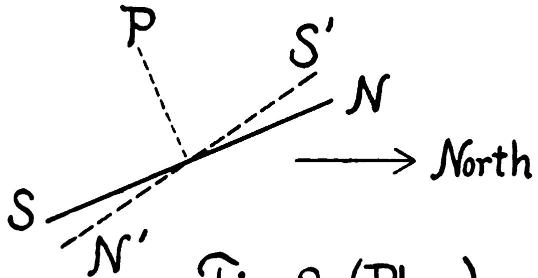

Fig. 2 (Plan)

The upper system having the greater capacity for retaining magnetism, whatever diminution of magnetism is necessary has been made on this system. The lower system is first magnetized to saturation by a large magnet. Next the magnetism of the upper system is brought to a slight excess by making judicious passes with the large magnet at a distance of 1 cm. or less. Finally, the magnetism of the upper system is diminished very gradually by stroking the individual magnets with minute bits of magnetized needles set in marked wooden handles, the free north-seeking or south-seeking poles projecting slightly.

Suppose that, the normal to the mirror pointing west, the upper system is stroked on its east side by the little magnets.

(1) Strengthening south-seeking poles inclines normal north.
(2) Strengthening north-seeking poles inclines normal south.
(3) Weakening south-seeking poles inclines normal south.
(4) Weakening north-seeking poles inclines normal north.

In case the relative position of the planes has been very much disturbed by these gentle strokings, if, for instance, the normal to the mirror turns strongly to the south after weakening the south-seeking poles of the upper system, it may be necessary to strengthen the south-seeking poles of the lower system by the large magnet; or if the reverse disturbance of the planes has occurred and the normal inclines strongly to the north, the north-seeking poles of the lower system may have to be strengthened. The reasons for the above rules will be evident from the figure. Thus in the application of (3) pressure from the east at *S* opens the angle between the planes of the system, as in fig. 2. The resultant systems, *N′S* and *NS′*, are developed, which tend to set in the plane of the meridian. At the same time the directive force of *NS* has been weakened. In (4) pressure being applied on the east side of *N*, the opening of the angle between the planes of *NS* *N′S′* is the opposite of that in fig. 2, and the resultant magnetic systems, *SN′*, *S′N*, having their south-seeking poles on the east side of the mean plane, tend to rotate *P* to the north, the directive force of *NS* being diminished as before. In (1) the pressure tends to open out the angle as in fig. 2 and swing *P* to the south, but the directive force of *NS* being increased, tends in the opposite direction, and it might not be certain which would prevail. The rule, however, is the result of experience.

A single hollow cylindrical magnet 10 mm. long, suspended by a very fine quartz fiber, made a half vibration in 0.286 sec. (specific magetism = 135 C. G. S. units per gram of steel). The average of a system of ten magnets, as prepared for the galvanometer was 0.386 sec. (square = 0.149). In 1892 the astatic condition of the needle was such as to give a half vibration in 10 seconds, which in 1894 had diminished to 8 seconds, no retouching having been made during the interval. The ratios

$$0.149 : 10^2 = 1 : 671$$
$$0.149 : 8^2 = 1 : 429$$

would represent the relative directive powers of the partially astatic system at these dates, were it not that the magnetic moments are not inversely proportional to the squares of the times of vibration in a needle as heavily damped as this. The weight of the magnets being about 0.2 gram, and specific magnetism 800 Gaussian units $\left(\frac{\text{mm.}^{\frac{5}{2}}\ \text{mgr.}^{\frac{1}{2}}}{\text{sec.}}\text{ per mgr. of steel}\right)$, or 80 C. G. S. units per gram of steel, the magnetic moment, if all the magnets pointed one way, would be

$$0.2 \times 80 = 16 \text{ C. G. S.}$$

Astaticized, if the law of inverse squares of the times were followed, the magnetic moments would be

$$(1892) \qquad 16 \div 671 = 0.0238 \text{ C. G. S.}$$
$$(1894) \qquad 16 \div 429 = 0.0373$$

the ratio of which is

$$0.0238 \div 0.0373 = 0.638.$$

But the galvanometer constant, determined by an entirely independent method, does not differ much from inverse proportionality to the times of vibration, the field magnetization being the same in all cases, a result which is to be attributed to the damping as already noted.

The absolute value of the galvanometer constant, together with a calibration of the galvanometer scale, has been made in the following way: The battery current, measured by an independent standardized galvanometer, was passed through the delicate galvanometer, shunted by 84 cm. of heavy copper wire, 0.494 cm. in diameter, reading the deflections of the sensitive instrument with various extra resistances interposed in the circuit; and the resistances of shunt and battery were determined separately.

The battery resistance was measured by the "half deflection method" in which d_1 being the deflection through extra resistance R_1, d_2 is a deflection, half as great, obtained with extra resistance R_2. The battery resistance is $r = R_2 - (2\,R_1 + G)$, where G is the resistance of the shunted galvanometer, here practically zero. Three trials gave:

$d_1 = 500$ div., $R_1 = 460$ ohms, $d_2 = 250$ div., $R_2 = 204$ ohms, $r = 52$ ohms.
$d_1 = 400$ “ $R_1 = 584$ “ $d_2 = 200$ “ $R_2 = 258$ “ $r = 68$ “
$d_1 = 300$ “ $R_1 = 794$ “ $d_2 = 150$ “ $R_2 = 369$ “ $r = 56$ “

Average battery resistance = 59 ohms.

The resistance of the shunt was measured by short-circuiting it by a plug, when the very low resistance of the heavy brass connections of the resistance box became the sole shunt, reducing the galvanometer deflection almost to zero. The current from a single cell of gravity battery, reduced by 1,100 ohms, was passed directly through the galvanometer thus shunted, the galvanometer connections being opened and closed by a key. The valuation of the deflections was made by repeating with shunt short-circuited, and either of the smaller (hundredth and fiftieth ohm) coils in its place, using the formula for shunts:

$$\frac{C_1}{C} = \frac{S}{S + G}$$

where C_1 is the current through the galvanometer, C the total current, S the resistance of the shunt, and G that of the galvanometer. In the present case, however, since S is very small relatively to G, the ratio $\frac{S}{S+G}$ is substantially equal to $\frac{S}{G}$, which may be used instead.

Putting in the plug also short-circuits the thermopile currents from junctions of unlike metals, and changes of temperature cause these to vary, but by reversing the galvanometer connections, their effects may be partly eliminated. With a high-resistance galvanometer this trouble would cease.

Galvanometer connections, direct or reversed, are denoted by *d* and *r* in the following table. Shunt, open or plugged (that is, short-circuited), is signified by *o* and *p*. The comparison deflections, in the last column but one, correspond to a hundredth-ohm coil, and to half the deflections given by two different fiftieth-ohm coils.

TABLE 8.

Plugged.	Open.	Plugged.	Shunt.	Plugged.	Open.	Plugged.	Shunt.	0.01 ohm.	Res. shunt.
rp	*ro*	*rp*		*dp*	*do*	*dp*			
div.	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*ohm.*
− 3.0	−15.0	− 3.0	− 17.9	+22.5	+33.1	+20.4	+ 35.4	162.9	$\frac{13.6\times0.01}{163}$
− 2.7	−18.2	− 7.0		+20.0	+35.5	+21.2		153.2	
− 4.1	−20.6	− 6.0	−(−4.3)	+21.8	+37.6	+18.8	− 20.8	172.0	
− 3.3	−17.9	− 5.3	− 13.6	+21.4	+35.4	+20.1	+ 13.6	162.7	=0.00083
dp	*do*	*dp*		*rp*	*ro*	*rp*			
+11.7	+36.9	+15.2	+ 34.6	+ 2.9	−20.0	− 5.2	− 20.4	133.4	$\frac{19.3\times0.01}{145}$
+12.4	+33.0	+18.0		+ 1.2	−19.2	− 4.8		142.1	
+13.5	+33.8	+18.7	− 14.9	+ 1.6	−22.0	− 3.7	− (−1.4)	159.5	
+12.5	+34.6	+17.3	+ 19.6	+ 1.9	−20.4	− 4.6	− 19.0	145.0	=0.00133
Heavy copper shunt reversed and solidly clamped.									
dp	*do*	*dp*		*dp*	*do*	*dp*			
+11.0	+26.6	+13.9	+ 29.0	+13.9	+34.0	+21.0	+ 32.3	122.1	$\frac{15.2\times0.01}{144}$
+ 9.9	+31.5	+15.2		+15.2	+31.0	+20.3		118.6	
+11.5	+29.0	+15.5	− 12.9	+15.5	+31.9	+21.8	− 18.0	147.8	
								147.8	
								162.8	=0.00109
+10.8	+29.0	+14.9	+ 16.1	+14.9	+32.3	+21.0	+ 14.3	163.8	
rp	*ro*	*rp*		*rp*	*ro*	*rp*			
− 3.2	−20.0	− 5.0	− 21.5	−12.0	−31.2	−20.9	− 31.9		$\frac{16.3\times0.01}{144}$
− 2.0	−23.2	− 7.5		−16.0	−33.0	−17.2			
− 2.5	−21.2	− 6.2	−(−4.4)	−13.6	−31.4	−19.1	−(−16.5)		
− 2.6	−21.5	− 6.2	− 17.1	−13.9	−31.9	−19.1	− 15.4	143.8	=0.00113
Mean resistance of heavy shunt									=0.00109

In the galvanometer tests, induction currents gave a stronger backward swing than happens in the bolometric work where there is a continuous current only slightly varied by the resistance changes due to radiation. Consequently deflections have been computed by a formula:

$$\delta = d - \frac{e_1 + e_2}{2}$$

where e_1 is the reading before connecting, d the extreme of the swing given by the current, and e_2 is obtained from three successive swings of the needle, after the current is broken, by the formula:

$$e_2 = \frac{n_2^2 - n_1 n_3}{2n_2 - n_1 - n_3}$$

A single series follows in full (extra resistance, 270 ohms).

TABLE 9.

e_1	d	n_1	n_2	n_3	e_2	$\frac{e_1+e_2}{2}$	δ
+2	+405	—111	+35	—3	+4.9	+3.5	+401.5
0	403	—117	+30	—5	+1.7	+0.9	402.1
+1	397	—116	+30	—5	+1 8	+1.4	395.6
0	389	—114	+29	—6	+0.9	+0.5	388.5
+1	389	—115	+26	—7	—0.7	+0.2	388.8
0	388	—113	+30	—6	+1.2	+0.6	387.4
+1	395	—115	+31	—3	+3.4	+2.2	392.8
—1	396	—118	+27	—9	—1.8	—1.4	397.4
—1	396	—113	+33	—2	+4.8	+1.9	394.1
+2	396	—111	+30	—4	+2.6	+2.3	393.7
+0.5	+395.4	—114.3	+30.0	—5.0	+1.9	+1.2	+394.2

The ratio of the current in the galvanometer to that in the shunt is taken as 1:18,800. The mean results of five series are given.

TABLE 10.

Series.	Extra resistance plus battery.	Current in shunt.	Deflection. δ	Current in galvanometer.	Galvanometer constant. 1 div.=
	Ohms.	*Ampere.*	*Divisions.*	*Ampere.*	*Ampere.*
1	1,159	0.00735	114.7	3.91×10^{-7}	3.40×10^{-9}
2	609	0.01399	211.6	7.44	3.51
3	429	0.01986	298.5	10.56	3.53
4	329	0.02590	394.2	13.78	3.50
5	269	0.03167	484.2	16.85	3.48
Mean galvanometer constant, 1 div. $= 3.48 \times 10^{-9}$ ampere.					

It will be seen that the galvanometer constant is the same in all parts of the scale, as nearly as can be determined by this method. There have been some indications that the instrument is a very little more sensitive for small deflections, less than 20 div.; but as the amount is hardly appreciable, and seems to vary with the slightest change in the hanging of the needle, no correction has been applied.

Since the cylindrical magnets do not lie in the central plane of the coils, the induction damping is larger than usual, and departure from a logarithmic decrement was to be anticipated in the vibrations. The means of the five series, similar to that given in full in Table 9, are:

TABLE 11.

e_1	d	n_1	n_2	n_3	e_2	$\frac{e_1+e_2}{2}$	δ
+0.3	+115.1	— 31.2	+ 8.6	—1.7	+0.5	+0.4	+114.7
+0.2	+211.7	— 60.3	+15.5	—4.1	±0.0	+0.1	+211.6
—0.2	+298.9	— 86.3	+23.3	—4.9	+1.0	+0.4	+298.5
+0.5	+395.4	—114.3	+30.0	—5.0	+1.9	+1.2	+394.2
+0.6	+484.0	—141.6	+34.6	—9.3	—0.9	—0.2	+484.2

The next table contains the amplitudes (a_1 a_2 a_3) of successive vibrations and the logarithms of their ratios.

TABLE 12.

a_1	a_2	a_3	$log \frac{a_1}{a_2}$	$\frac{1}{2} log \frac{a_1}{a_3}$
146.3	39.8	10.3	0.5651	0.5766
272.0	75.8	19.6	0.5550	0.5713
385.2	109.6	28.2	0.5560	0.5678
509.7	144.3	35.0	0.5460	0.5816
625.6	176.2	43.9	0.5503	0.5769
Mean logarithmic decrements.			0.5545	0.5749

The air damping appears to be tolerably uniform, since there is no marked relation between the logarithmic decrements and the amplitudes; but the influence of induction currents is seen in the change of the decrement in successive periods.

The needle is suspended by a single fiber of silk, 33 cm. long from the suspending piece to the copper ring. The entire fiber is about 40 cm. long, is tied to the copper ring of the needle by a loose square knot, and, at its other end, carries a weight equal to that of the needle. At the outset the galvanometer is inverted, and the counterpoise hanging freely, the silk fiber is allowed to stretch and untwist until it comes into a normal state; then the galvanometer is set up in its usual position, the fiber passing over the edge of the suspending piece, but not being fastened to it. The suspending piece is finally adjusted until the needle hangs centrally. As thus prepared the silk fiber has very little tendency to twist, the image from the free but undisturbed needle seldom wandering during the day more than the few divisions to be expected from the diurnal variation of the magnetic declination.

The bolometric equilibrium can not be maintained perfectly in a room of changing temperature, and some means of bringing the null point to any part of the scale at pleasure is desirable. Variation of the field by weak magnets, although objectionable, has been used to some extent. The change of field necessary in order to push the null point from one end of the scale to the other was determined by measuring the deflection from a constant impulse.

TABLE 13.

Starting point.	Mean of 10 deflections.	Percentage of deflection at 100.
Divisions.		*Per cent.*
0	+87.61±0.34	101.9
100	+85.03±0.38	100.0
200	+84.99±0.39	98.1
300	+81.27±0.51	96.1
400	+80.83±0.72	94.3

In order that the deflections may be comparable within 2 per cent., the null point should not be changed by more than 100 divisions during the observations. To avoid the necessity of more than a slight change of field the electric current has been allowed to flow through the bolometer for at least twenty-four hours before commencing observations, and the room has been kept at a nearly constant temperature.

The cover glass of the galvanometer case has optically plane parallel surfaces, and the carefully figured mirror gives a sharp image, permitting readings by estimation to a tenth of a division.

In some of the experiments I have made the exposure to radiation by pulling cords, at the same time reading the galvanometer; in others, it has been necessary to have an assistant shift some part of the apparatus at the word of command.

SCREENS.

The bolometer chamber has been used with two different openings: First, a wide aperture, limited by a series of graduated circular card-board diaphragms, the outermost 1.19 inches (3.02 cm.) in diameter, 3.92 inches (9.96 cm.) from the bolometer, giving an angular aperture of 17° 16′. Second, a smaller aperture, the case being further protected by triple tin-plate screens, with circular openings: the outermost 1.15 inches (2.92 cm.) in diameter, 12.3 inches (31.24 cm.) in front of the bolometer (angle 5° 21′); the middle and limiting aperture 1.02 inches (2.59 cm.) in diameter, 11.3 inches (28.70 cm.) from the bolometer, giving an angular aperture of 5° 10′.

The ratio of the squares of the angular apertures is 11.17 : 1, but the observed efficiencies have the ratio 8.96 : 1, which is adopted. I can only conjecture that the difference is due to the reflection of the bolometer's radiation by the polished tin plate, and the retention of a larger proportion of the heat received from radiation when the aperture is partly closed by the metal screen; but no experiments have been tried to test the hypothesis.

In order to transform the measures made in arbitrary units of a scale into absolute units of radiant energy, and at the same time to furnish a check on the constancy of the measuring instruments, the bolometer has been exposed from time to time to the radiation from blackened copper screens containing water at different temperatures.

The unit of radiant energy employed is that which I have elsewhere called the *radim*,[*] "representing a unit quantity of heat, namely, one gram-water-degree-centigrade heat-unit, lost *as radiation* per square centimeter of surface per second of time, by a heated body, or transmitted by the ether as an equivalent amount of radiant energy through a normal section of 1 sq. cm. in one second of time."

The standard of radiation adopted is that of blackened copper at 100° C. to a surface of the same material at 0° C., filling the hemisphere, which, according to the measures of Dr. J. T. Bottomley may be taken as 0.0126 radim. Measured radiations between any other temperature limits have been reduced to the standard by multiplying by a factor obtained by dividing the difference of radiations at the given limits, as read from the standard curve (derived from Table B, p. 270, *Astrophysical Journal*, Vol. 8), by 0.0126. The deflections are further reduced to a standard battery current of 0.033 ampere, corresponding to 100 div. of the battery galvanometer.

The radiating surface, seen through the full aperture of 17° 16′, occupied

$$(50 \times \tan 8^\circ 38')^2 \times \pi = 181.06 \text{ sq. cm.},$$

the center of the radiating surface being placed 50 cm. from the bolometer, and its plane normal to the line of sight. The mean angle with the line of sight of a circle in the radiating surface at mean distance is

$$\alpha = \tan^{-1} \frac{r\sqrt{2}}{2 \times 50} = 6^\circ 7'.7,$$

where the radius of the bounding circle is

$$r = 50 \times \tan 8^\circ 38';$$

and the mean distance of the surface is

$$d = \frac{r\sqrt{2}}{2 \sin \alpha} = 50.319 \text{ cm.}$$

The bolometer of 0.19 sq. cm. receives of the total radiation, assuming equable emission at all inclinations, the fraction

$$\frac{0.19}{2\pi d^2} = 0.000\ 011\ 957$$

and the standard radiation received by the bolometer with full aperture is

$$E_1 = 0.000011957 \times 181.06 \times 0.0126.$$

$$= 0.000\ 027\ 278 \text{ radim.}$$

The smaller aperture has been used with radiators but little removed. The radiation through this aperture, of 1.295 cm. radius, is virtually that of a surface of like area, 5.2685 sq. cm., and the standard radiation received by the bolometer is

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[*] The Probable Range of Temperature on the Moon, *Astrophysical Journal*, vol. 8, p. 271, December, 1898.

$$E_2 = \frac{0.19}{2\,\pi \times (28.7)^2} \times 5.2685 \times 0.0126.$$

$$= 0.000\ 002\ 437 \text{ radim.}^*$$

The efficiency of the radiation coming through this smaller aperture, however, has been shown to be 25 per cent. greater than that of an equal amount of radiant energy passing through the large aperture (p. 21).

I proceed to give screen comparisons and the valuation of standard deflections.

March 12, 1892.

First Series.

Battery galvanometer 100 div.
Hot screen 69°.8 C., computed radiation 0.0154 radim.
Cold " 9°.5 C., " " 0.0083 "
Radiation reduced from standard:

$$E = E_2 \times \frac{71}{126} = 0.000\ 001\ 373 \text{ radim.}$$

$\delta = 35.43$ div. (mean of 10, small aperture); 1 div. = 0.000 000 0388 radim.

Standard deflection, on standard radiation, and with full aperture $= 35.43 \times 8.96 \times \frac{126}{71} =$ 563.4 div.

Second Series.

Battery galvanometer 100 div.
Hot screen 69°.4 C., computed radiation 0.0153 radim.
Cold " 11°.8 C., " " 0.0085 "

$$E = E_2 \times \frac{68}{126} = 0.000\ 001\ 315 \text{ radim.}$$

$\delta = 30.94$ div. (mean of 10, small aperture); 1 div. = 0.000 000 0425 radim.

Standard deflection (full aperture) $= 30.94 \times 8.96 \times \frac{126}{68} = 513.7$ div.

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* The quantities E_1 and E_2 are introduced purely as reduction factors, and do not represent exactly the quantities of *normal* radiation received by the actual bolometer, although the latter may easily be derived from them.

The total radiation from each unit of radiating surface to a hemisphere is to the fraction of radiation emitted per sq. cm. at angle (i_1) with the normal, and received on an element of the hemisphere (δs), in the proportion

$$2\,\pi\,r \times \sum_0^{\frac{1}{2}\pi} \cos i \sin i\, \delta i : \cos i_1\ \delta s.$$

In the present case, cos i_1 may be taken as unity, δs (the area of the bolometer) is 0.19 sq. cm., $\delta i = \frac{1}{2}$ degree, and $r = 28.7$ cm.

The numerical value of

$$2\,\pi\,r \times \sum_0^{\frac{1}{2}\pi} \cos i \sin i\, \delta i = \pi\,r \sum_0^{\frac{1}{2}\pi} \sin 2i \times \frac{\pi\,r}{360}$$

is 2587.7, and the bolometer receives $0.19 \div 2587.7 = \frac{1}{13619}$ of the entire radiation.

For any other radiator than lampblack, the relative radiation, $\rho \times \phi\,(i)$, must be considered. The value of ρ has been determined for air in the present research for nearly normal emission, but $\phi\,(i)$ remains unknown.

July 28, 1892.

Battery galvanometer 97 div.
Hot screen 76°.0 C., computed radiation 0.0162 radim.
Cold " 33°.8 C., " " 0.0107 radim.

$E = E_2 \times \frac{55}{126} = 0.000\ 001\ 073$ radim.

$\delta = \frac{24.54 \times 100}{97} = 25.30$ div. (mean of 10, small aperture); 1 div. = 0.000 000 0424 radim.

Standard deflection (full aperture) $= 25.30 \times 8.96 \times \frac{126}{55} = 519.3$ div.

March 10, 1893.

Battery galvanometer 98 div.
Hot screen 99°.0 C., computed radiation 0.0200 radim.
Cold " 0°.8 C., " " 0.0078 "

$E = E_1 \times \frac{122}{126} = 0.000\ 026\ 412$ radim.

$\delta = 515.9 \times \frac{100}{98} = 526.4$ div. (mean of 10, full aperture); 1 div. = 0.000 000 0502 radim.

Standard deflection (full aperture) $= 526.4 \times \frac{126}{122} = 543.7$ div.

March 3, 1894.

Battery galvanometer 101 div.
Hot screen 98°.7 C., computed radiation 0.0200 radim.
Cold " 0°.7 C., " " 0.0078 "

$E = E_1 \times \frac{122}{126} = 0.000\ 026\ 412$ radim.

$\delta = \frac{487.4 \times 100}{101} = 482.6$ div. (mean of 10, full aperture); 1 div. = 0.000 000 0547 radim.

Standard deflection (full aperture) $= 482.6 \times \frac{126}{122} = 498.4$ div.

March 30, 1894.

Battery galvanometer 95 div.
Hot screen 99°.1 C., computed radiation 0.0200 radim.
Cold " 29°.4 C., " " 0.0103 "

$E = E_1 \times \frac{97}{126} = 0.000\ 021\ 000$ radim.

$\delta = 364.2 \times \frac{100}{95} = 383.4$ (mean of 10, full aperture); 1 div. = 0.000 000 0548 radim.

Standard deflection (full aperture) $= 383.4 \times \frac{126}{97} = 498.0$ div.

July 30, 1895.

Battery galvanometer 95 div.

First Series.

Hot screen 98°.3 C., computed radiation 0.0198 radim.
Cold " 23°.7 C., " " 0.0097 "

$E = E_1 \times \frac{101}{126} = 0.000\ 021\ 866$ radim.

$\delta = 456.1 \times \frac{100}{95} = 480.1$ (mean of 10, full aperture); 1 div. = 0.000 000 0456 radim.

Standard deflection (full aperture) $= 480.1 \times \frac{126}{101} = 598.9$ div.

Second Series.

Hot screen 91° C., computed radiation 0.0187 radim.
Cold " 24° C., " " 0.0097 "

$E = E_1 \times \frac{90}{126} = 0.000\ 019\ 484$ radim.

$\delta = 401.7 \times \frac{100}{95} = 422.8$ (mean of 5, full aperture); 1 div. = 0.000 000 0461 radim.

Standard deflection (full aperture) $= 422.8 \times \frac{126}{90} = 591.9$ div.

Third Series.

Hot screen 85° C., computed radiation 0.0177 radim.
Cold " 24° C., " " 0.0097 "

$E = E_1 \times \frac{80}{126} = 0.000\ 017\ 319$ radim.

$\delta = 354.8 \times \frac{100}{95} = 373.5$ (mean of 5, full aperture); 1 div. = 0.000 000 0464 radim.

Standard deflection (full aperture) $= 373.5 \times \frac{126}{80} = 588.3$ div.

Fourth Series.

Hot screen 77° C., computed radiation 0.0164 radim.
Cold " 24° C., " " 0.0097 "

$E = E_1 \times \frac{67}{126} = 0.000\ 014\ 505$ radim.

$\delta = 300.6 \times \frac{100}{95} = 316.4$ (mean of 5, full aperture); 1 div. = 0.000 000 0458 radim.

Standard deflection (full aperture) $= 316.4 \times \frac{126}{67} = 595.0$ div.

The last four series were made to test the validity of the mode of reduction for E, which is sufficiently accurate for its purpose. The two series of March 12, and that of July 28, 1892, being founded on rather small deflections taken with the small aperture, are less reliable than the others. They give a mean value of 1 div. = 0.000 000 0412 radim, corresponding to $0.000\ 000\ 0412 \times \frac{5}{4} =$ 0.000 000 0515 radim for the full aperture. The observation of March 10, 1893, with full aperture, gave 1 div. = 0.000 000 0502 radim, and the galvanometer constant may be assumed uniform for the first year (1892–93), when its value in amperes was measured. On March 3, and March 30, 1894, larger radiation was required to give a deflection of one division, namely, 1 div. = 0.000 000 0548 radim, or 7½ per cent. greater than in 1892–93, the vibration of the needle having meanwhile become 20 per cent. more rapid, or the squares of the times 36 per cent. smaller; and finally, in July, 1895, the time of vibration being the same as in 1894, 1 div. = 0.000 000 0460 radim, or 7½ per cent. less than in 1892–93. The last change is perhaps attributable to simultaneous changes in the magnetism of the needle and in the magnetic field, but as the field was not measured independently, no correction is available.

The variation of the radiator's surface is a possible source of error in these standardizings. To guard against it, a uniform procedure has been followed. The screens are of copper, painted dead black, with a very thin coat. Before using, this surface is lightly smoked with a fresh coat of soot, uniformly distributed. From experience with such a surface, it does not seem probable that variations of more than 2 or 3 per cent. are to be anticipated; but it is not asserted that this standard fulfilled the ideal of an absolutely black body. After the measures of July 30, 1895, an effort was made to carry the radiant emissivity of the hot screen somewhat nearer its maximum value, by repeated smokings, while the screen was temporarily filled with cold water, until a coat of soot ½ mm. thick had been deposited. The mean standard deflection of 593.5 was thereby raised to 620.7, or by 4.6 per cent.

If the variations are attributed to errors, and all observations have equal weight, 1 div. = 0.000 000 0490 ± 0.000 000 0010 radim, but in the author's opinion, it is best to accept the variation as a fact and to take the valuations as given at the stated epochs, whence, for full aperture, we have the following radiant values:

(1892–93) 1 div. = 0.000 000 0509 radim.
(1894) 0.000 000 0548 "
(1895) 0.000 000 0460 "

For the small aperture, the corresponding values are four-fifths of these—

(1892–93) 1 div. = 0.000 000 0412 radim.
(1894) 0.000 000 0438 "
(1895) 0.000 000 0368 "

PSYCHROMETER FACTOR.

The water-vapor in the air experimented upon has been measured by a stationary psychrometer, checked occasionally by a dew-point apparatus. The usually adopted formula for a ventilated or a sling psychrometer is:

$$f_1 = f_2 - 0.000\ 67\ (t - t')\ H,$$

where f_1 = the pressure of water-vapor at the dew-point, f_2 = the vapor pressure at the temperature of the wet bulb, and H = the barometer reading, may be in either millimeters or inches of mercury; but t and t', the dry and the wet-bulb readings, are in centigrade degrees.

The statement is made in books on the subject that the numerical factor by which the difference $(t - t')$ is to be multiplied, may need to be doubled in a closed room; but since every psychrometer must vary according to the kind of muslin with which the wet bulb is covered, and according to the disposition of objects around it, the factor should be determined by experiment.

Two windows on opposite sides of the room were left open, producing a gentle circulation of the air. Dew was formed on a polished tin-plate vessel in which water was cooled by ice, or heated at pleasure. The cold water half filled the vessel, and the contrast between upper and lower halves was noted.

(1)

$$\begin{array}{lr} & ^\circ\text{C.} \\ \text{Dew formed at} & +6.8 \\ \text{Dew evaporated at} & +9.4 \end{array}\left.\begin{array}{c} \\ \\ \\ \end{array}\right\}\ \begin{array}{r} ^\circ\text{C.} \\ \text{Mean } +8.1 \end{array}$$

(2)

$$\begin{array}{lr} & ^\circ\text{C.} \\ \text{Dew formed at} & +7.8 \\ \text{Dew evaporated at} & +8.9 \end{array}\left.\begin{array}{c} \\ \\ \\ \end{array}\right\}\ \begin{array}{r} ^\circ\text{C.} \\ \text{Mean } +8.4 \end{array}$$

Observed dew-point = $+8^\circ.3$ C. = $+46^\circ.9$ F.
Corresponding psychrometer readings:

(1)

$$\begin{array}{lrcr} & ^\circ\text{F.} & & ^\circ\text{C.} \\ \text{Dry bulb} & 77.1 & = & 25.0 \\ \text{Wet bulb} & 63.2 & = & 17.3 \end{array}\left.\begin{array}{c} \\ \\ \\ \end{array}\right\}\ \begin{array}{lrcr} & ^\circ\text{F.} & & ^\circ\text{C.} \\ \text{Difference} & 13.9 & = & 7{:}7 \end{array}$$

(2)

$$\begin{array}{lrcr} & ^\circ\text{F.} & & ^\circ\text{C.} \\ \text{Dry bulb} & 77.6 & = & 25.3 \\ \text{Wet bulb} & 63.7 & = & 17.6 \end{array}\left.\begin{array}{c} \\ \\ \\ \end{array}\right\}\ \begin{array}{lrcr} & ^\circ\text{F.} & & ^\circ\text{C.} \\ \text{Difference} & 13.9 & = & 7.7 \end{array}$$

The windows were now closed.

(In ten minutes.)

(3)

$$\begin{array}{lrcr} & ^\circ\text{F.} & & ^\circ\text{C.} \\ \text{Dry bulb} & 78.8 & = & 26.0 \\ \text{Wet bulb} & 66.4 & = & 19.1 \end{array}\left.\begin{array}{c} \\ \\ \\ \end{array}\right\}\ \begin{array}{lrcr} & ^\circ\text{F.} & & ^\circ\text{C.} \\ \text{Difference} & 12.4 & = & 6.9 \end{array}$$

(In thirty minutes.)

(4)

$$\begin{array}{lcc} & {}^\circ\text{F.} & {}^\circ\text{C.} \\ \text{Dry bulb} & 79.9 = & 26.6 \\ \text{Wet bulb} & 68.5 = & 20.3 \end{array}\Big\} \text{ Difference } \begin{array}{cc} {}^\circ\text{F.} & {}^\circ\text{C.} \\ 11.4 = & 6.3 \end{array}$$

(In sixty minutes.)

(5)

$$\begin{array}{lcc} & {}^\circ\text{F.} & {}^\circ\text{C.} \\ \text{Dry bulb} & 80.1 = & 26.7 \\ \text{Wet bulb} & 68.1 = & 20.0 \end{array}\Big\} \text{ Difference } \begin{array}{cc} {}^\circ\text{F.} & {}^\circ\text{C.} \\ 12.0 = & 6.7 \end{array}$$

Open windows.

By Hazen's Tables (Fahrenheit, p. 64) for the temperature 77° F. and dew-point 47°, the depression of the wet bulb (ventilated) is 17°.25 F. The observed depression was 13°.9 F., whence $(t-t')$ must be multiplied by

$$\text{factor} = \frac{17.25}{13.9} = 1.24$$

For the temperature 77°.5 F. (same dew-point), the depression by the table is 17°.50 F., and the observed depression 13°.9 F.

$$\text{factor} = \frac{17.50}{13.9} = 1.26$$

Windows closed.

For the temperature 79° F. (same dew-point as before), by table, depression = 18°.5 F., observed, 12°.4,

$$\text{factor} = \frac{18.5}{12.4} = 1.49$$

For the temperature 80° F. (same dew-point), by table, depression = 19°.0 F., observed, 11°.4,

$$\text{factor} = \frac{19.0}{11.4} = 1.67$$

For the temperature 80° F. (same dew-point), the final observation gave depression 12°.0,

$$\text{factor} = \frac{19.0}{12.0} = 1.58$$

The first condition (two windows open) is seldom realized in bolometric work, and never unless the outside air is nearly calm, which was not the case during the above experiments. In winter the windows are usually closed during bolometric observations, this being necessary to prevent air currents and sudden variations of temperature around the bolometer. The room in which the experiments were made has a floor space of 60 sq. m., and is connected with other rooms, all heated by a hot-air furnace, and well ventilated. In warm summer weather a single window is commonly open. These things being so, since the mean of the above determinations gives 1.45 for the multiplier, 1.5 is adopted as the working factor by which $(t - t')$ has been multiplied in finding the dew-point by the unventilated psychrometer, and by Hazen's Tables. With this explanation, further details will be omitted, and only the results of psychrometric measures will be stated.

Three successive pieces of apparatus have been used for measures of atmospheric radiation:

(*a*) A pair of open radiant cylinders.
(*b*) Hot air ascending from a furnace flue.
(*c*) A closed radiant cylinder with movable disk.

The horizontal air column in line with the bolometer is to be considered as composed of two parts. The portion between the bolometer and the front of the radiating apparatus is of nearly the same temperature as the bolometer, and acts chiefly by absorbing. The portion of air within the apparatus both radiates and absorbs, but the differential effect is radiative, and for the sake of distinction the first part may be called the absorbent, the second the radiant layer.

Psychrometer readings, as usually reduced, are stated in pressures of water-vapor on the standard of the mercury gage (millimeters of mercury), or as a weight of water per unit volume of air (grams per cubic meter); but in considering the absorbent or radiant effects it is more convenient to express the amount of water-vapor as a depth of equivalent liquid water penetrated by the line of sight within the limits of the radiative or absorbent column. For example, a column of air 100 meters long and 1 square decimeter in section occupies 1 cubic meter, and if its water-vapor be all condensed upon a normal section, a liquid layer 1 millimeter thick will be produced for every 10 grams of vapor contained in the air column. If the volume of air has the form of a cube 1 meter on an edge, the layer of condensed water being distributed over a normal section of 1 square meter, will have a depth of 0.01 mm. for every 10 grams per cubic meter, the depth of water being directly proportional to the length of the air column multiplied by the absolute humidity. This mode of expression relates solely to the quantity of water present. Nothing is predicated as to the quality of its absorption or radiation, which may vary widely according to the physical state in which this definite quantity of water exists.

The chief atmospheric constituent affecting radiation being water-vapor, it is necessary to consider the air depths (d), and the equivalent layers of liquid water (w) in d, for each gram of water-vapor per cubic meter of air, involving the following constants in the successive pieces of apparatus.

TABLE 14.

	Absorbent layer.	Radiant layer.
Apparatus a	d = 13.2 inches = 33.5 cm. w = 0.000 0335 cm.	36.4 inches = 92.5 cm. 0.000 0925 cm.
Apparatus b_1	d = 10.0 inches = 25.4 cm. to 7.0 inches = 17.8 cm. $w = \begin{cases} 0.000\ 0254 \text{ cm.} \\ 0.000\ 0178 \text{ cm.} \end{cases}$	16.0 inches = 40.6 cm. 0.000 0406 cm.
Apparatus b_2	d = 16.25 inches = 41.2 cm. to 11.5 inches = 29.2 cm. $w = \begin{cases} 0.000\ 0412 \text{ cm.} \\ 0.000\ 0292 \text{ cm.} \end{cases}$	3.5 inches = 8.9 cm. to 7.0 inches = 17.8 cm. $\begin{cases} 0.000\ 0089 \text{ cm.} \\ 0.000\ 0178 \text{ cm.} \end{cases}$
Apparatus c	d = 14.8 inches = 37.6 cm. w = 0.000 0376 cm.	4.25 to 60 inches = 10.8 to 152.4 cm. Contents of cylinder usually dry or nearly so.

DESCRIPTION OF METHOD (A) AND APPARATUS.

The ideal aimed at in the disposition of the apparatus was to obtain a concave surface of polished silver at constant temperature, having the bolometer strips at its center of curvature, and completely filling the circular openings in the multiple bolometer screens of polished metal. Radiations proceeding from the bolometer toward the concave mirror (distant about 125 cm.) would then be directly returned, except as affected by absorption, while rays from any objects in front of the mirror, but outside of the cone of rays from the bolometer to the mirror's edge, could not possibly be reflected upon the bolometer.

The bolometer being at the bottom of the deep cylindrical cavity of its ebonite case,* protected from air currents by internal diaphragms, and further shielded by the multiple metallic screens already mentioned, it was arranged to transpose the volume of air intervening between the mirror and the outer bolometer screen, and to substitute volumes of hot or cold air so rapidly that the temperature of the bolometer should remain unaffected save by the feeble radiation of the gas, the temperature of the concave mirror being expected to remain appreciably unchanged in the brief interval of exposure, owing to the small absorption of radiation by silver and the continual circulation of water within the metallic walls, as will be now described.

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* See Plate 2, accompanying Prof. S. P. Langley's article "On Hitherto Unrecognized Wave-lengths," in *Am. Journ. of Sci.*, vol. 132.

The mirror was made of silver-plated copper, so as to be both a good conductor and a poor radiator, but owing to the thinness of the copper and its yielding quality it was found difficult to preserve the spherical figure. The mirror formed the central portion of the front face of a rectangular vessel containing water at the temperature of the room, and on testing its figure, certain small portions, as viewed from the position of the bolometer, were found to reflect light from a lamp flame placed outside, but close alongside the aperture of the bolometer screen. It was evident, therefore, that some of these distorted surfaces might reflect enough radiation from the interior blackened walls of the cases containing the hot and cold air to entirely vitiate the result.

It was recognized from the start that the radiating power of a gas is so greatly at a disadvantage, compared with the emissive power of a solid, that the least exposure of hot or cold metal in front of the bolometer would give thermal indications, which might very easily be greater than those to be expected from the short air column available for experiment. The failure to obtain a perfect spherical reflector which should also be a good conductor, without going to greater expense than was deemed advisable, led to a partial modification of the original plan in the coating of the mirror with lampblack. The layer of soot being very thin, must retain (it was supposed) substantially the temperature of its metallic backing, in spite of its being a good absorbent of radiation,* while the greater part of the blackened spherical surface remains incapable of reflecting outside rays to the bolometer, owing to its shape, except in a weak, diffusive way, and the specular reflections from the small distorted areas are rendered ineffective owing to the feeble reflecting power of lampblack and the obstruction of rays reflected from silver in traversing the discontinuous particles of powdered carbon.

The first experiments were made to compare results with silver and with lampblack for a background, in order to get a knowledge of the magnitude of the errors which are to be guarded against, and of the legitimate radiations at our disposal.

The movable air chambers were cylindrical vessels of tin plate, 8 inches in diameter, and 36.4 inches long, provided with diaphragms of circular aperture, 6 inches apart, and graduated from an opening of 2 inches at the end next to the bolometer, to one of 7 inches at the further extremity, adjacent to and circumscribing the mirror face. The inner surfaces of the air chambers were blackened, and apertures were provided at the middle, and 8 inches from each end, for the insertion of thermometers, whenever the temperature was read. The bulbs were, of course, drawn outside the limits of the radiating space during actual work. The air cylinders were contained in tanks 3 feet long, and 1 foot square in transverse section, the cylinders projecting slightly at either end, and being unjacketed at these ends, but being otherwise completely surrounded by the contents of the tanks, which contained either hot or cold water, or a freezing mixture. The tanks were mounted on a rolling carriage, moving between guides, and could be drawn to an accurately adjusted stop on one side or the other, so as to bring the longitudinal axis of either air chamber in line with the bolometer and the center of the mirror; and this could be accomplished by the observer at the galvanometer by pulling a cord passing over pulleys to the movable carriage, thus transposing the air vessels, while simultaneously observing and recording the galvanometer readings.

The outermost aperture of the bolometer's multiple metallic screen, 1.15 inches in diameter, at 12.3 inches from the instrument, was concentric with the 2-inch aperture of the near end of the air chamber which was 13.2 inches from the bolometer, and since the angular aperture of the opening in the screen, as seen from the bolometer, namely 5°.35, was much smaller than those of the air chamber, which were 8°.67 for the near aperture, and 8°.07 for the further opening in front of the mirrior, there was no danger that any portion of the walls of the air chamber could be directly observed.

Since in shifting the air chambers to and fro, the larger or 7-inch aperture remained always nearly in juxtaposition with the silvered face of the fixed water tank, very little air could escape at this end, and that which entered at the 2-inch aperture was prevented from having free circulation by the internal diaphragms. It was found that with an excess of 60° C., the excesses of either of the internal thermometers of the air chamber above the temperature of the outside air seldom differed from the mean by as much as 5 per cent. The temperature gradient of the central axis of the air chamber has therefore usually been quite moderate.

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* How far this supposition is invalidated will be shown in the sequel.

The following temperature readings for a single day, March 15, 1892, are given in proof of this statement:

TABLE 15.

Excess of hot cylinder above outside air temperature as inferred from the mean of the three thermometers.	Mean variation of three internal thermometers.
° C.	° C. *Per cent.*
67.8	± 0.6 = 0.9
70.1	± 0.8 = 1.1
69.5	± 0.9 = 1.3
66.9	± 1.9 = 2.8
65.0	± 0.4 = 0.6
61.0	± 1.0 = 1.6
65.4	± 2.1 = 3.2
61.8	± 1.8 = 2.9
60.7	± 0.8 = 1.3
56.3	± 1.4 = 2.5

There being no constant order in the relative excesses of the three thermometers, their mean has been adopted as the average temperature of the air column.

CORRECTION FOR THE MAGNETIC EFFECT OF THE APPARATUS DURING MOTION IN METHOD (A).

The positions of stone piers, and other necessities of the case, compelled the placing of the principal apparatus in a position where the shifting of its iron parts feebly, but appreciably, affected the very sensitive galvanometer. Comparisons of the galvanometer readings in extreme positions of the two air cylinders were therefore made, under otherwise identical conditions, to obtain the magnetic effect upon the galvanometer, due to the movement of these considerable masses of tinned iron at an average distance of 12 feet from the magnetic needle.

Experiment of July 29, 1892.

All parts of the apparatus were substantially at the temperature of the room. No conceivable cause, therefore, existed for any temperature deflection. Moreover, variation of the thermal conditions by making the blackened silver screen hot, but leaving the intermediate air cylinders cool and equal in temperature, gave practically the same result, though obviously a less trustworthy one, since it is difficult to maintain the temperature of the hot screen constant.

Exposures were made by alternating west and east cylinders—that is, by bringing the central axis of each cylinder in turn into the line of collimation of the bolometer. To eliminate galvanometer drift, each pair of readings with west cylinder in line was compared with the intermediate reading with east cylinder in line.

	° C.
Temperature of west cylinder (near thermometer),	29.3
Temperature of west cylinder (middle thermometer),	29.3
Temperature of east cylinder (rear thermometer),	29.0
Temperature of east cylinder (middle thermometer),	27.8
Temperature of blackened water-filled screen,	27.8

TABLE 16.

First series.				Second series.			
West cylinder in line.	Mean west.	East cylinder in line.	Deflection east.	West cylinder in line.	Mean west.	East cylinder in line.	Deflection east.
			div.				*div.*
101.2				99.0			
97.3	99.3	102.8	+3.5	95.0	97.0	101.9	+4.9
98.0	97.7	102.0	+4.3	96.9	96.0	100.1	+4.1
98.2	98.1	101.0	+2.9	99.2	98.1	101.8	+3.7
96.1	97.2	101.0	+3.8	97.0	98.1	101.5	+3.4
98.5	97.3	101.0	+3.7	96.6	96.8	102.0	+5.2
97.3	97.9	101.8	+3.9	97.9	97.3	101.3	+4.0
93.9	95.6	99.0	+3.4	96.4	97.2	100.7	+3.5
96.0	95.0	100.2	+5.2	95.9	96.2	100.9	+4.7
98.8	97.4	100.1	+2.7	94.2	95.1	98.5	+3.4
98.8	98.8	101.6	+2.8	93.7	94.0	98.0	+4.0
Mean,			+3.62	Mean,			+4.09

The probable errors of the two series being ± 0.16 div. and ± 0.14 div., equal weights may be given to them, and their common mean applied with opposite signs, according as the change of position is from west to east, or the reverse, whence the mean magnetic deflection by presentation of east cylinder = + 3.86 div.; by presentation of west cylinder = − 3.86.

OBSERVATION OF AIR RADIATION BY METHOD (A).

The radiation measures with the first apparatus follow. The sensitiveness of the galvanometer during these experiments remained unchanged. The astaticism, checked from day to day, continued constant. The time of a half vibration of the needle, chronographically determined, was 9.7 seconds.

A comparison of deflections with polished silver and blackened reflector showed that the former were from two to three times the greater, proving, as had been anticipated, that the reflections from the distorted surface of the silver were larger than the air radiation to be measured. It is only necessary, then, to consider those measures in which, the bolometer being directed to the concave blackened surface, the alternate interposition of hot or cold columns of air has given small but consistent positive deflections from the heated air. There remains only the uncertainty whether, in spite of the backing of conducting copper and water, the outer radiant layer of the lampblack may not change temperature by contact with the hot and cold air. This point will be considered in connection with the results of other methods.

Each interposition of hot air has been made between a pair of cold ones whose mean is taken for comparison, and the movements have been regularly timed in such a way as to allow the galvanometer needle just time enough to complete its swing, 11 consecutive readings on the cold air and 10 intermediate ones on the hot air, forming a series, as in the example at constant temperature in Table 16.

Experiments of March 10, 1892.

West cylinder heated.

East cylinder surrounded by refrigerating mixture of snow and salt.

TABLE 17.

	Before first series.	Between series.	After second series.	Mean first series.	Mean second series.	Deflections (hot).	
						First series.	Second series.
						div.	*div.*
Temperature of bolometer	15°.0 C.	14°.4 C.	14°.5 C.	14°.7 C.	14°.5 C.	15.0	13.4
" " screen	20°.0 C.	19°.6 C.	19°.2 C.	19°.8 C.	19°.4 C.	17.3	11.2
" " room	12°.3 C.	12°.2 C.	12°.1 C.	12°.3 C.	12°.2 C.	15.2	15.8
Pressure of atmosphere	729.0 mm.	(At 0° C.)		729.0 mm.	729.0 mm.	12.9	15.4
Dew-point	5°.6 C.	5°.6 C.	5°.6 C.			13.1	14.4
Pressure of water vapor				6.78 mm.	6.78 mm.	12.9	15.9
Water per cubic meter				7.03 grams.	7.03 grams.	11.0	16.5
Temperature of hot air	57°.1 C.	54°.2 C.	48°.8 C.	55°.7 C.	51°.5 C.	17.1	15.6
" " cold "	—12°.2 C.	—11°.3 C.	— 9°.5 C.	—11°.8 C.	—10°.4 C.	11.2	15.4
" excess	69°.3 C.	65°.5 C.	58°.3 C.	67°.5 C.	61°.9 C.	13.4	13.1
Mean deflections						13.91	14.67

The probable error of the mean of the first series is ± 0.51 div., and of the second, ± 0.37 div. The battery galvanometer stood at 99 div., and the deflections, reduced to the standard current (100 div.) and corrected for the negative magnetic deflection of the west cylinder, become—

First series: $(+ 13.91 + 3.86) \div 0.99 = + 17.95$ div.

Second series: $(+ 14.67 + 3.86) \div 0.99 = + 18.72$ "

The mean temperature of the hot-air column was 39°.0 above that of the bolometer, and the cold air was 25°.7 below the instrument. The mean atmospheric pressure was 729 mm. and the force of water vapor 6.78 mm., equivalent to a layer of liquid water 0.000 236 cm. thick in the absorbent column, 33.5 cm. long.

Experiments of March 15, 1892.

West cylinder heated.

East cylinder surrounded by cool water of nearly the same temperature as the bolometer. Silvered reflector freshly blackened by smoking it over a smoky lamp flame.

TABLE 18.

	Before first series.	Between series.	After second series.	Mean first series.	Mean second series.	Deflections (hot).	
						First series.	Second series.
						div.	*div.*
Temperature of bolometer			8°.7 C.	8°.7 C.	8°.7 C.	16.1	13.6
" " screen		7°.9 C.	8°.0 C.	8°.0 C.	8°.0 C.	15.0	12.7
" " room	4°.4 C.	5°.2 C.	3°.1 C.	4°.8 C.	4°.2 C.	18.2	19.0
Pressure of atmosphere	738.4 mm.	(At 0° C.)		738.4 mm.	738.4 mm.	14.2	13.8
Dew-point	—10°.0 C.	— 8°.9 C.	— 7°.8 C.			14.2	7.7
Pressure of water vapor				2.35 mm.	2.55 mm.	15.7	12.9
Water per cubic meter				2.57 grams.	2.78 grams.	10.2	13.4
Temperature of hot air	73°.9 C.	72°.1 C.	68°.1 C.	73°.0 C.	70°.1 C.	10.2	12.9
" " cold "	+ 7°.9 C.	+ 7°.5 C.	+ 6°.8 C.	+ 7°.7 C.	+ 7°.2 C.	12.1	15.4
" excess	66°.0 C.	64°.6 C.	61°.3 C.	65°.3 C.	62°.9 C.	17.5	18.2
Mean deflections						14.34	13.96

The probable errors of the mean deflections are ± 0.61 div. and ± 0.60 div. Battery galvanometer = 102 div. Deflections reduced to standard and corrected:

First series: (+ 14.34 + 3.86) ÷ 1.02 = + 17.84 div.

Second series: (+ 13.96 + 3.86) ÷ 1.02 = + 17.47 "

The mean atmospheric pressure was 738.4 mm., and the mean force of water vapor 2.45 mm., equivalent to a liquid layer 0.000 090 cm. thick in the length of the absorbent column of air.

In the third and fourth series, the tank around the cold cylinder was filled with a mixture of snow and salt, giving as wide a range of temperature as the structure of the apparatus would permit.

TABLE 19.

	Before third series.	Between series.	After fourth series.	Mean third series.	Mean fourth series.	Deflections (hot).	
						Third series.	Fourth series.
						div.	div.
Temperature of bolometer	8°.7 C.		9°.3 C.	8°.9 C.	9°.2 C.	18.0	18.2
" " screen	8°.0 C.		8°.0 C.	8°.0 C.	8°.0 C.	15.2	17.8
" " room	4°.2 C.	5°.6 C.	6°.3 C.	4°.9 C.	6°.0 C.	21.3	20.9
Pressure of atmosphere	(Approximately.)			738 mm.		16.3	21.3
Dew-point	—3°.3 C.	—3°.1 C.	—1°.1 C.			18.6	17.7
Pressure of water vapor	3.59 mm.	3.64 mm.	4.22 mm.	3.62 mm.	3.93 mm.	24.0	17.3
Water per cubic meter	3.84 grams.	3.90 grams.	4.48 grams.	3.87 grams.	4.19 grams.	21.5	21.9
Temperature of hot air	69°.6 C.	67°.4 C.	67°.0 C.	68°.5 C.	67°.2 C.	18.4	23.2
" " cold "	—15°.2 C.	—15°.0 C.	—14°.4 C.	—15°.1 C.	—14°.7 C.	16.9	18.8
" excess	84°.8 C.	82°.4 C.	81°.4 C.	83°.6 C.	81°.9 C.	19.9	18.6
Mean deflections						19.01	19.57

The probable errors are ± 0.60 div. for the third, and ± 0.51 div. for the fourth series, and the corrected deflections are—

Third series: (+ 19.01 + 3.86) ÷ 1.02 = + 22.42 div.

Fourth series: (+ 19.57 + 3.86) ÷ 1.02 = + 22.97 "

The mean air pressure was about 738 mm., and the mean force of vapor 3.78 mm., equivalent to a liquid layer of water 0.000 135 cm. deep in a length of 33.5 cm.

Experiments of July 29, 1892.

Object: The measurement of radiation from warm air, containing considerable water vapor, for comparison with results obtained in cold, dry weather. Also a determination of the absorption of this radiation by glass.

East cylinder the hot one, the magnetic influence of moving masses being therefore the reverse of that in previous measures. West cylinder surrounded by melting ice. Silvered reflector, forming the background, freshly coated with soot.

The first and fourth series are comparable with previous measures, varying only in the higher range of temperature and the larger quantity of water. In the second and third series, the aperture of the bolometer case was covered by a pane of window glass 3.15 mm. thick, which transmits about 76 per cent. of the total apparent solar radiation, and 14 per cent. of that from the moon, and which is practically impervious to rays of greater wave-length than 4½ microns, giving us, in the absence of spectrobolometric measures, a preliminary approximation to the region of the spectrum in which the radiation lies.

TABLE 20.

	Before first series.	After second series.	After fourth series.	Adopted for 1 and 2.	Adopted for 3 and 4.
Temperature of bolometer	32°.0 C.			32°.0 C.	32°.0 C.
" " screen	29°.7 C.	29°.8 C.	30°.0 C.	29°.8 C.	29°.9 C.
" " room	32°.6 C.		32°.0 C.	32°.5 C.	32°.2 C.
Pressure of atmosphere	730.74 mm.	(At 0° C.)	731.76 mm.	731.0 mm.	731.5 mm.
Dew-point	23°.9 C.		23°.3 C.		
Pressure of water vapor				21.63 mm.	21.63 mm.
Water per cubic meter				21.06 grams.	21.06 grams.
Temperature of hot air	93°.2 C.	89°.1 C.	89°.5 C.	91°.2 C.	89°.3 C.
" " cold "	+6°.5 C.	+8°.2 C.	+8°.2 C.	+7°.4 C.	+10°.6 C.
" excess	86°.7 C.	80°.9 C.	80°.9 C.	76°.5 C.	78°.7 C.

DEFLECTIONS FROM HOT-AIR COLUMN.*

	First series.	Second series.	Third series.	Fourth series.
	div.	*div.*	*div.*	*div.*
	21.1	10.1	3.8	26.9
	18.5	3.4	2.8	27.8
	25.0	7.4	4.5	22.5
	23.6	5.9	5.3	20.6
	24.8	4.1	6.4	24.4
	26.3	9.1	4.7	21.9
	29.0	4.3	6.0	22.5
	24.0	4.5	6.2	21.7
	24.0	4.5	6.4	24.6
	29.3	2.6	7.0	24.4
Mean deflections	24.56	5.59	5.31	23.73

* Series 1 and 4 without glass, 2 and 3 through glass.

The probable errors of the means, in the order of the series, are ± 0.65 div., ± 0.57 div., ± 0.31 div., ± 0.53 div.; and the battery galvanometer reading being 96.5 div., the deflection, corrected for the positive magnetic deflection of the east cylinder, and reduced to the standard current, are—

First series: $(+24.56 - 3.86) \div 0.965 = +21.45$ div.
Second series: $(+\ 5.59 - 3.86) \div 0.965 = +\ 1.79$ "
Third series: $(+\ 5.31 - 3.86) \div 0.965 = +\ 1.50$ "
Fourth series: $(+23.73 - 3.86) \div 0.965 = +20.59$ "

The glass used transmits

	μ
31 per cent. of radiation of wave-length,	1.9
18 " " " " " " "	3.1
8 " " " " " " "	4.3

Not over $\frac{1}{20}$ of the radiation from a surface of lampblack, at the temperatures with which we are dealing, lies in this region of very limited glass transmission. Most of the fraction, indeed, will be near the longest wave-length mentioned, and 0.1 is a fair index of its average transmission by glass, so that, if we say that it is hardly possible for $\frac{1}{200}$ of the rays from the lampblack background to escape absorption by glass, the statement is justifiable. If the deflection of about 1½ div. through glass is genuine, it must be of atmospheric origin. As the absorption of glass is a discontinuous one, at any rate in this part of the spectrum, it is possible that the absorption of a linear gaseous spectrum whose lines or bands do not coincide with those of glass, may be much less than for a continuous spectrum like that of lampblack, and that 8 per cent. transmitted in the present case may represent a fraction of gaseous radiation either of shorter wave-length than 4½ microns, or of greater wave-length than the region of lampblack emission, comparatively unabsorbed.

In proof of the statement that the absorption of glass is discontinous, it may be mentioned that rays in a small part of the lampblack spectrum from a glass prism, in the region near 2μ, were found to be three times as transmissible by glass as in the same region from a rock-salt prism, showing that certain rays which are present in the rock-salt prismatic spectrum, have been entirely cut off in the spectrum from the glass prism, and that those rays which remain pass through glass with comparative freedom.

The mean atmospheric pressure in the experiments of July 29, was 731.3 mm., the vapor pressure 21.63 mm., and the equivalent layer of liquid water in the absorbent air column was 0.000 706 cm., that in the radiant hot-air column being about twice as great, and five to seven times as great as in the experiments of March 15. If the greater amount of water in the summer air has increased its radiative power, the deflections in series 1 and 4, July 29, ought to exceed those in series 3 and 4, March 15; indeed, without any change in radiant emissivity, some increase of radiation was to be anticipated, because, although the temperature-excesses were smaller in July, the range was on a part of the temperature scale farther from absolute zero, and where the differential radiation, as shown in the figures for lampblack (Table 21), may be expected to be greater. The summer deflections are actually a little smaller, indicating that the radiation measured has been, to a considerable extent, that of the lampblack background, which has suffered greater absorption by water in summer. The following tables exhibit these relations, the last columns being stated in absolute radiant units. The radiating volume of air has the form of a truncated cone whose angle is 5°.35, the length of the frustum and depth of the radiating layer being 92.5 cm., the diameter of its smallest section 3.1 cm., and that of its largest and most distant section 11.8 cm., while the volume of the frustum is 4,510 cub. cm. The measured radiation approaches the half of what might be expected from surfaces of lampblack at the given temperatures.

TABLE 21.

Date and series.	Temperatures.		Computed lampblack radiation to a hemisphere.	Ratio to lampblack radiation from 100° to 0° C. r	Computed lampblack radiation through small aperture. $E_2 \times r$
	Cent. t	Absol. T			
	°	°	*Radim.*		*Radim.*
March 10, 1892 (1)	56 —12	329 261	$\left.\begin{matrix}.0135\\.0065\end{matrix}\right\}.0070$	$\frac{70}{126}=.556$	0.000 001 355
" (2)	52 —10	325 263	$\left.\begin{matrix}.0129\\.0066\end{matrix}\right\}.0063$	$\frac{63}{126}=.500$	0.000 001 214
March 15, 1892 (1)	73 8	346 281	$\left.\begin{matrix}.0158\\.0082\end{matrix}\right\}.0076$	$\frac{76}{126}=.603$	0.000 001 469
" (2)	70 7	343 280	$\left.\begin{matrix}.0155\\.0080\end{matrix}\right\}.0075$	$\frac{75}{126}=.595$	0.000 001 450
" (3)	69 —15	342 258	$\left.\begin{matrix}.0153\\.0063\end{matrix}\right\}.0090$	$\frac{90}{126}=.714$	0.000 001 740
" (4)	67 —15	340 258	$\left.\begin{matrix}.0150\\.0063\end{matrix}\right\}.0087$	$\frac{87}{126}=.690$	0.000 001 682
July 29, 1892 (1)	91 7	364 280	$\left.\begin{matrix}.0186\\.0080\end{matrix}\right\}.0106$	$\frac{106}{126}=.841$	0.000 002 050
" (4)	.89 11	362 284	$\left.\begin{matrix}.0184\\.0084\end{matrix}\right\}.0100$	$\frac{100}{126}=.794$	0.000 001 935

For the equivalent water depths in the first three columns of the next table, reductions of water vapor in terms of mass (m), stated in grams per cubic meter, have first been made from the indicated vapor pressures (p) and barometric pressures (B), reduced to the freezing point, using the formula—

$$m = 1\,000\,000 \times \frac{p}{B} \times \frac{0.000\,8041}{1 + 0.003\,670t}$$

where t is the centigrade temperature of the hot or cold air in the radiant air column. These masses have then been multiplied by the factor (w) in Table 14. The liquid depths are given in millionths of a centimeter.

TABLE 22.

Date and series.	Liquid water in—			Corrected deflection. δ	Temperature excess.	Measured radiation.
	Radiant layer.		Absorbent layer.			
	Hot.	Cold.				
				Divisions.	° *C.*	*Radim.*
March 10, 1892 (1)	567	200	236	17.95	67.5	0.000 000 740
" (2)	574	223	236	18.72	61.9	0.000 000 771
March 15, 1892 (1)	186	230	93	17.84	65.3	0.000 000 735
" (2)	204	250	93	17.47	62.9	0.000 000 720
" (3)	291	153	130	22.42	83.6	0.000 000 924
" (4)	317	158	140	22.97	81.9	0.000 000 946
July 29, 1892 (1)	1473	754	706	21.45	76.5	0.000 000 884
" (4)	1480	916	706	20.59	78.7	0.000 000 848

EXAMINATION OF PROFESSOR HUTCHINS' HYPOTHESIS "THAT RADIATION TAKES PLACE ONLY WHEN THERE IS A FALL OF TEMPERATURE WITHIN THE LIMITS OF MOLECULAR ACTION."

In a research on the Radiation of Atmospheric Air (*Am. Journ. of Sci.*, vol. 43, p. 357–363, May, 1892) Prof. C. C. Hutchins endeavors to determine the effect of varying the thickness of a radiating layer of air. "A flat sheet-iron pipe was made 100 cm. long, 10 cm. wide, and 2.5 cm. thick." This pipe was supported in an inclined position and heated by Bunsen burners. "The air exit was from a pair of jaws, one fixed, one movable, so that the thickness of the air column at its escape could be regulated at pleasure. * * * The results were recorded as the amount of galvanometer deflection per degree of $t - t'$. With openings less than 1 cm. no difference in the amount of radiation can be detected. With larger openings a small increase is observed."

	cm.	cm.	cm.	cm.
Opening,	0.5	1	2	3
Deflection per degree,	0.193	0.195	0.245	0.259

The conclusion drawn is "that radiation is very largely from the surface of contact between the hot and cold air, which seems to indicate that a heated gas absorbs all or nearly all those rays that it itself emits, and that radiation takes place only when there is a fall of temperature within the limits of molecular action" (p. 363, *loc. cit.*). The values given show that when the air aperture was enlarged sixfold, radiation only increased in the ratio of 259 to 193, or by 34 per cent.; but it seems to me that the inferences are not warranted. The uprushing jet draws cool air from the sides and mingles it with the hot air, and the effect of this admixture is proportionally greater in a narrow jet, so that until the aperture is considerably greater than those used by Professor Hutchins, the cooling by admixture very nearly neutralizes any gain from greater depth in the line of sight. The viscosity of air prevents an indefinite extension of the mixing. A jet of more than a certain depth at a given altitude above the nozzle will have its temperature lowered by mixture only at the borders of the ascending air column, the central part of the cross section of the heated air having a constant temperature. Except for absorption of its own radiation by the air any further increase of depth will then give radiant values greater in approximate proportionality to the thickness of the layer. Professor Hutchins appears to have been deceived by an eye observation, which he describes on page 359 (*loc. cit.*). "By burning touch paper at the bottom of the tube, the lamps beneath being lighted, the shape of the column of air from the nozzle can be inspected at leisure by reason of the dense smoke that issues with it, and by filling the throat of the nozzle it can be given such a shape that the column of heated air will preserve uniform dimensions for a considerable distance from its exit." On the strength of this observation of a uniformity of cross section in the ascending air column, a constant velocity and identical composition of the jet "for a considerable distance from its exit" seems to have been inferred; but this is incorrect, since, as I shall show, the thermal gradient of a cross section of the air column is not only not a single valued quantity in a given instance, but the form of the gradient varies with the aperture of the nozzle, and this implies variation of velocity and more or less admixture of cool air.

DESCRIPTION OF METHOD B.

Method A having been discredited, or at least having come under suspicion, no attempt was made to extend it to air columns of other dimensions; but, instead, the bolometer was pointed to a cold screen entirely separated from the hot air which issued from an effluent chamber of wood (fig. 3) placed over the hot-air flue from the furnace, whose register could be opened or closed by pulling cords.

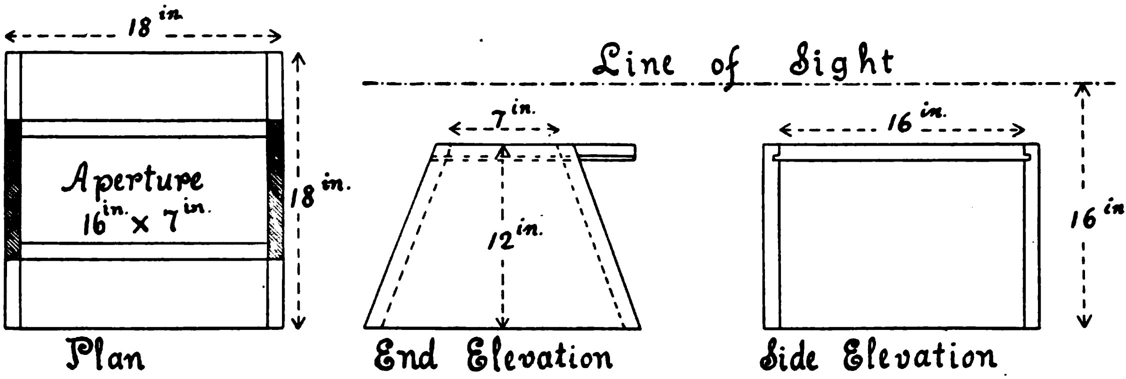

Fig. 3

The aperture through which the hot air issues has a length of 16 inches (40.6 cm.) and a breadth of anything less than 7 inches (17.8 cm.), as determined by the position of a sliding panel. By rotating the wooden casing through 90°, either the longitudinal or the transverse axis of the aperture can be made parallel to the line of sight, giving different depths of radiating air without altering the section and general condition of the air stream. By means of the sliding panel both the depth and sectional area of the air stream may be varied.

The hot air within the wooden effluent chamber does not entirely escape upon shutting the register. The temperature within the aperture was 17°.6 higher than that of the air in the line of sight, 4 inches (10.2 cm.) above the aperture, when the register was closed; but with the register open, the strong current of hot air maintained a uniform temperature in the vertical direction, although there was a considerable thermal gradient in the horizontal direction along the transverse axis.

Experiments of February 23, 1893.

The bolometer was placed 18 inches (45.7 cm.) from a vertical line through the center of the aperture. When the aperture (16 by 6 inches) was end-on, the cone of rays included the diameter of the air vein in the most distant section. The temperature of the air around the bolometer strips, as determined by a thermometer bulb inside the bolometer case, was 10°.8 C. at the beginning, and 9°.8 at the close. Successive readings of the temperature of the air of the room at intervals of some minutes were 4°.3, 4°.5, 5°.0, 4°.3, 4°.5. The temperatures on which the deflections depend are those of the air in the line of sight. Three thermometers were placed in the longitudinal axis of the aperture: (*a*) 3 inches from its farther end and 5 inches from the center, (*b*) at the center, and (*c*) 3 inches from the nearer end. The temperature within the aperture (register shut) was 24°.0. The thermometers, elevated into the line of sight, had a mean temperature of 6°.4 which is that of the cold air.

In the hot air, the readings were—

	First Series.			Second Series.		
	°		°	°		°
(*a*)	55.8	Excess,	49.4	57.0	Excess,	50.6
(*b*)	56.2		49.8	59.2		52.8
(*c*)	56.0		49.6	50.5		44.1
		Mean excess,	49.6		Mean excess,	49.2

The thermal gradient of the transverse diameter of the air vein is represented, on the average, by the following series:

49°
46° 46°
30° 30°
15° 15°
0 Excesses. 0

The thermometers were here an inch apart.

The average temperatures of successive sections on either side of the longitudinal axis are: 47°.5, 38°.0, 22°.5, 7.°5; and as the line of sight, with side presentation, penetrates all of these layers equally, the mean temperature of the radiant air in the second experiment is

$$(47.5 + 38.0 + 22.5 + 7.5) \div 4 = 28^{\circ}.9\ \text{C.}$$

In determining the mean temperature for the end-on presentation of the first experiment, no great refinement of computation is needed, and the section may be roughly summarized by fourths, as indicated in fig. 4.

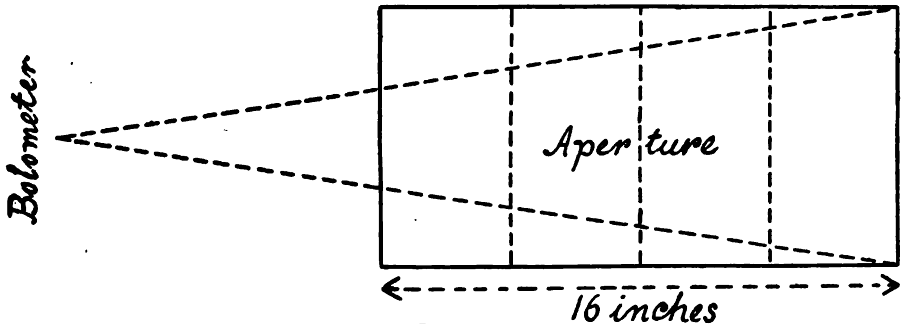

Fig. 4 (Plan)

In end-on presentation it is to be noted that, although the aperture has a width of 6 inches, the heated air spreads to a width of about 8 inches at the level of the line of sight, and the bolometer with its widest angular opening takes in the whole of this width at the distance of the farther end of the aperture, as shown in the diagram.

The most distant quarter of the air vein may be divided into eight vertical layers, 1 inch thick, and having the average temperatures just given. Cutting these layers by a horizontal cylinder which includes the extreme width, the areas of the successive transverse sections, counting from the axial ones, are:

(1) $1.571-1.076=0.495$
(2) $1.076-0.614=0.462$
(3) $0.614-0.227=0.387$
(4) 0.227

$\text{Sum}=\frac{1}{2}\pi=1.571$

To obtain the mean temperature of the entire section, these areas may be treated as weights, giving as the temperature of the most distant fourth of the air vein—

$$t_4 = \frac{47.5 \times .495 + 38.0 \times .462 + 22.5 \times .387 + 7.5 \times .227}{1.571}$$
$$= 32^{\circ}.8\ C.$$

Similarly, the next nearer quarter of the air vein may be considered as composed of six vertical layers of the central hotter region cut by an including cylinder, the areas of successive sections being—

(1) 1.571 — 0.916 = 0.655
(2) 0.916 — 0.343 = 0.573
(3) 0.343

The mean temperature of the next to the most distant fourth is then—

$$t_3 = \frac{47.5 \times .655 + 38.0 \times .573 + 22.5 \times .343}{1.571}$$
$$= 38^{\circ}.6\ C.$$

The nearer half of the air vein may be assumed to consist of the four inner vertical layers and the areas of their sections—

(1) 1.571 — 0.614 = 0.957
(2) 0.614

The mean temperature of the first and second fourths of the air vein is:

$$\frac{t_1 + t_2}{2} = \frac{47.5 \times .957 + 38.0 \times .614}{1.571}$$
$$= 43^{\circ}.8\ C.$$

The final mean is, for first experiment—

$$(32.8 + 38.6 + 43.8 + 43.8) \div 4 = 39^{\circ}.7\ C.$$

The observed galvanometer deflections were as follows:

TABLE 23.

First series (aperture end-on).	Second series (aperture sidewise).
div.	*div.*
11.8	4.0
9.9	1.7
12.2	3.1
6.9	2.9
6.3	0.0
11.8	3.8
14.5	2.3
12.2	1.5
9.2	4.2
8.0	5.3
Mean = 10.28 ± 0.62	Mean = 2.88 ± 0.34

Multiplying the mean temperatures by the depths of the radiating air layers, assuming these to be proportional to the dimensions of the aperture in the direction of the line of sight, the computed air radiations and their ratio are—

$$\left.\begin{array}{ll} (1) & 16\times 39.7=635.2 \\ (2) & 6\times 28.9=173.4 \end{array}\right\}\cdots\cdots\frac{173.4}{635.2}=0.273$$

The observed ratio is—

$$2.88 \div 10.28 = 0.280$$

the radiation for the greater depth being only a trifle less than its proportion according to the product of depth and temperature.

The battery galvanometer read 96 div. Reduced to standard current and stated in absolute units the radiations become—

(Depth, 40.6 cm.) Radiation = 10.71 div. = 0.000 000 545 radim.
(" 15.2 cm.) " = 3.00 div. = 0.000 000 153 "

For comparison with the results of the previous method, these deflections have to be reduced to the smaller aperture by dividing by 8.96, giving—

(Depth, 40.6 cm.) Radiation = 1.20 div. = 0.000 000 049 radim.
(" 15.2 cm.) " = 0.33 div. = 0.000 000 014 "

With a depth of 92.5 cm. and an excess of 65°, assuming proportionality of radiation to depth and temperature combined, an assumption which now seems justifiable in this first approximation, we might anticipate a radiation of—

$$0.000\ 000\ 049 \times \frac{92.5}{40.6} \times \frac{65}{40} = 0.000\ 000\ 181 \text{ radim.}$$

The measured radiation by Method A (Table 22) being about four times as great as this, we must conclude that something like three parts of the observed radiation in Method A were due to an excessively thin layer of warm radiating lampblack, with a small amount diffusively reflected by lampblack, and only one part to the hotter air.

The condition of the air in the experiments of this date was: Barometer, 724 mm.; dew-point, $-5^\circ.3$ C., corresponding to a vapor pressure of 3.09 mm., or to 3.34 grams of water per cubic meter. By Table 14 this represents the following depths of liquid water in the end-on presentation b_1 and the sidewise presentation b_2—

cm.
b_1, absorbent layer = 0.000 085
radiant " = 0.000 135 (cold)
" " = 0.000 118 (hot)
b_2, absorbent layer = 0.000 127
radiant " = 0.000 051 (cold)
" " = 0.000 046 (hot)

Experiments of February 25, 1893.

The bolometer was placed 15 inches (38.1 cm.) from a vertical line through the center of the aperture whose width was increased to 7 inches (17.8 cm.), giving a hot-air column a little over 9 inches wide at the level of the line of sight.

The longitudinal axis of the aperture in the end-on position lying east and west, thermometers were placed at the level of the line of sight—

(*a*) in the longitudinal axis of the air column 8 inches E. of center.
(*b*) " " " " " " " 6 " " " "
(*c*) " " " " " " " 3 " " " "
(*d*) " " " " " " " at the center.
(*e*) $2\frac{1}{2}$ inches north of longitudinal, 1 inch east of transverse axis.

To test the effect of the hot air remaining in the effluent chamber after the register was closed, the thermometers were read with the aperture alternately open and closed by a board cover.

	Aperture open.	Aperture closed.
	°	°
(*b*)	8.0	6.3
(*c*)	9.1	7.8
(*d*)	8.6	7.0
(*e*)	6.9	7.2

I have adopted for the temperature of the cold air (register closed, but aperture open)—

$$\frac{\frac{1}{3}(b+c+d)+e}{2} = 7^{\circ}.7\ C.$$

The temperature of the bolometer case was 10°.8, and the mean temperature of the air of the room was 6°.0.

The thermometer readings in the hot-air column in the first series were:

	°	
(*a*)	62.8	66°.4 = mean of temperatures at east end of longitudinal axis.
(*b*)	62.8	
(*c*)	68.8	
(*d*)	71.9	
(*e*)	44.2	

In the next series, thermometer (*e*) was transferred to a point in the longitudinal axis, 8 inches west of center—

		°	
East	(*a*)	45.0	Mean of temperatures in longitudinal axis = 66°.8.
	(*b*)	73.4	
	(*c*)	74.2	
Center	(*d*)	74.8	
West	(*e*)	66.6	

Thermometers (*a*) and (*e*) in this series, being near the point where the thermal gradient becomes very steep, are liable to vary considerably for a slight displacement of the vertical axis of the ascending air column.

The last two series of temperature readings have been taken with thermometers in the transverse axis of the hot-air column in positions at even inches from the center—

	Third series.	Fourth series.
	°	°
3 inches north of center	27.4	32.0
2 " " " "	....	63.0
1 inch " " "	....	70.2
Center	70.2	70.5
1 inch south of center	67.7	68.1
2 inches " " "	63.0	....
3 " " " "	47.8	....
4 " " " "	23.8	....
5 " " " "	....	13.4

These thermal sections show a spreading of the hot air, and its mixture with the surrounding cold air for an inch or so outside the original dimensions of the stream at the aperture of the effluent chamber. The heat, however, is nearly uniform for about 12 inches in the center of the longitudinal axis. Fig. 5 exhibits these thermal gradients to the eye—

Abscissæ = distances from center of air stream.
Ordinates = temperature-excesses (C.).
1 and 2 = series along longitudinal axis.
3 and 4 = " " transverse "

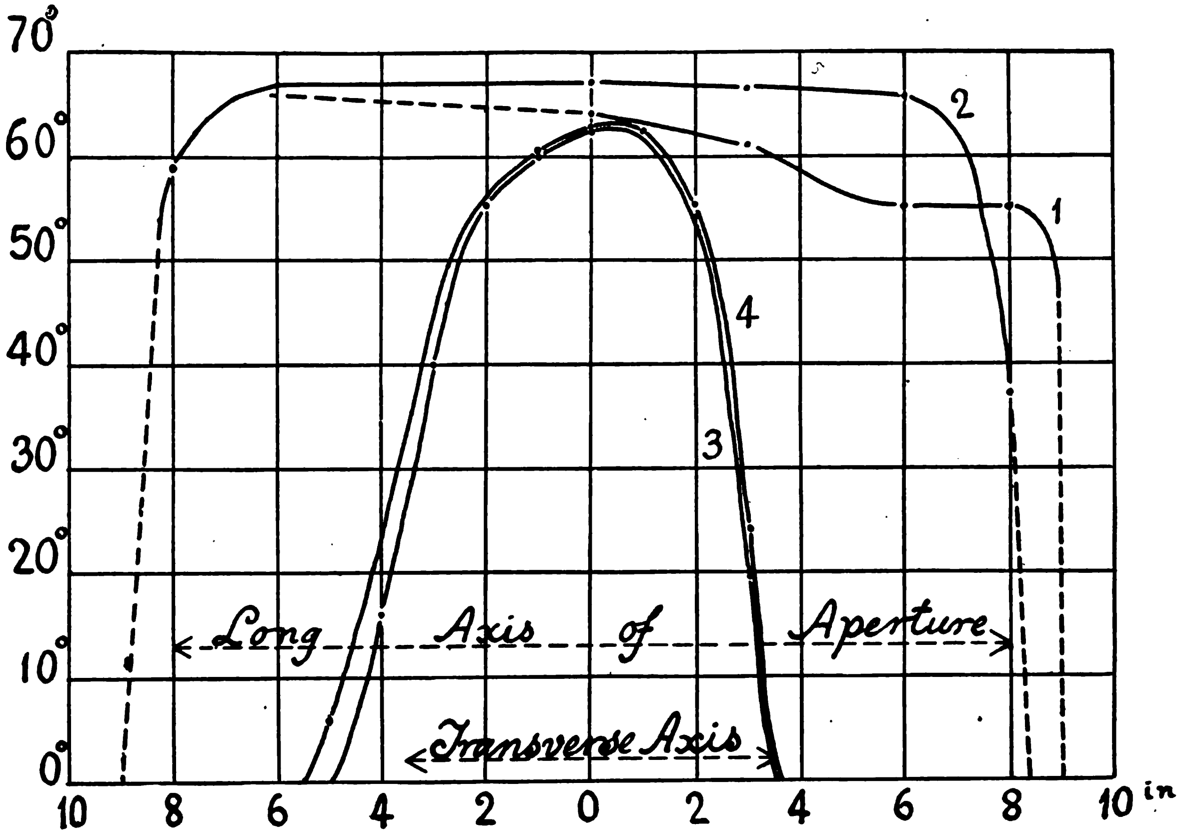

Fig. 5

The average thermal gradient of the transverse axis of the hot-air column may be represented by the following series:

63°
61° 61°
55° 55°
30° 30°
10° 10°
0 Excesses. 0

The average temperatures of successive sections on either side of the longitudinal axis are, 62°, 58°, 42°.5, 20°, 5°; and the mean temperature of the radiant air, when the line of sight agrees with the transverse axis of the air column, is—

$$(62 + 58 + 42.5 + 20 + 5) \div 5 = 37^\circ.5\ C.$$

Fig. 6 shows the disposition of bolometer, aperture, and air stream in the end-on presentation. In getting the mean temperature for this position, a small allowance has been made for the lack of symmetry of the air column. Dividing the air stream into a nearer and a more distant half, the mean temperature of the former may be taken as 61°. The more distant half varying from a mean of 61° at the nearest section to 46° at the most distant section, a rough approximation gives its mean temperature, in the part cut off by the cone of rays, as 55°, the final mean for the hot air radiating to the bolometer being 58° C.

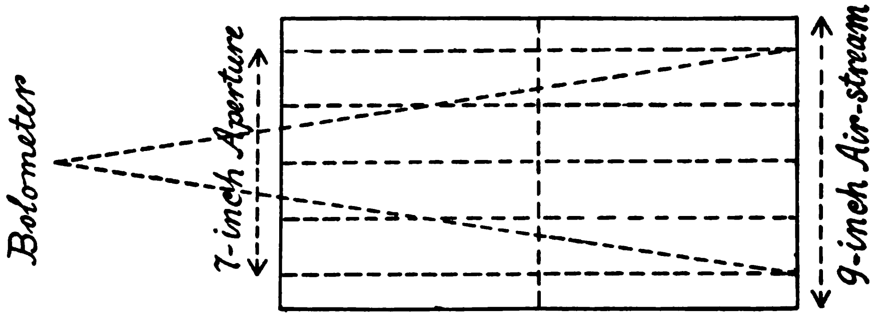

Fig. 6 (Plan)

Two widths of aperture, 7 and 3½ inches, were used with side presentation. In the end-on position the breadth of the aperture was constantly 7 inches and the length 16 inches. The observed galvanometer deflections follow:

TABLE 24.

First series, end on (16 inches).	Second series, side (7 inches).	Third series, end on (16 inches).	Fourth series, side (3½ inches).
div.	*div.*	*div.*	*div.*
5.2	4.2	7.6	1.7
9.7	4.6	9.7	—1.9
12.8	3.8	12.2	0.8
9.4	3.2	8.4	1.9
11.7	2.3	9.9	0.0
7.6	2.9	12.0	1.0
6.7	2.5	6.5	0.6
9.2	4.6	13.0	0.6
6.5	3.8	4.8	2.7
11.3	2.7	10.1	1.5
9.01±.56	3.46±.21	9.42±.59	0.89±.25

Observed radiation ratios.

Depth, 16	inches (40.6 cm.)	Deflection, 9.22	Ratio, 1.000
" 7	inches (17.8 cm.)	" 3.46	" 0.375
" 3.5	inches (8.9 cm.)	" 0.89	" 0.097

Assuming the radiant depths to be proportional to the dimensions of the aperture parallel with the line of sight and the radiations to be proportional to these depths, computation makes the air radiations and their ratios—

(1) and (3)	16 × 58 = 928	Ratio = 1.000
(2)	7 × 37.5 = 262.5	" = 0.283
(4)	3.5 × 37.5 = 131.3	" = 0.142

The battery galvanometer standing at 99 div., the reduction to standard current and absolute units gives—

Depth 40.6 cm. Radiation = 9.31 div. = 0.000 000 474 radim
" 17.8 cm. " = 3.49 div. = 0.000 000 178 "
" 8.9 cm. " = 0.90 div. = 0.000 000 046 "

The deflections in the fourth series are too small to be trusted. As shown by the transverse gradient, the ascending air has suffered a lateral displacement in the direction of the transverse axis, presumably from a side draft; and since the end-on deflections are notably smaller than on February 23, and relatively smaller than the corresponding side deflections which are not influenced by the displacement, it is probable that the temperature allowance made in the preceding computation is insufficient to compensate the actual variation at the time of radiation measurement. It will, of course, be understood that the observations of temperature and radiation were not synchronous, although made in immediate succession. Series 1 and 3 are therefore given half weight in the final mean.

The condition of the air, February 25, was as follows: Barometer, 726 mm., dew-point, $-1.9°$ C., corresponding to a vapor pressure of 3.98 mm., or to 4.24 grams of water per cubic meter. By Table 14, the depths of liquid water in the various air layers are—

	cm.		cm.	
Radiant depth	40.6	Absorbent layer	= 0.000 075	
		Radiant "	= 0.000 172	(cold)
		" "	= 0.000 142	(hot)
"	17.8	Absorbent "	= 0.000 124	
		Radiant "	= 0.000 075	(cold)
		" "	= 0.000 066	(hot)

TABLE 25.

Radiation of hot air (for small aperture) reduced to a depth of 1 meter.		
		Radim.
Feb. 23	(1)	$0.000\ 000\ 049 \div .406 = 0.000\ 000\ 121,\ t = 40$
	(2)	$0.000\ 000\ 014 \div .152 = 0.000\ 000\ 092,\ t = 29$
Feb. 25	(1, 3)	$0.000\ 000\ 043 \div .406 = 0.000\ 000\ 106,\ t = 58$
	(2)	$0.000\ 000\ 016 \div .178 = 0.000\ 000\ 090,\ t = 38$

Radiation of air at mean temperature-excess of 40° C. (Depth 1 meter.)
0.000 000 121
0.000 000 127
0.000 000 073
0.000 000 095
Mean = 0.000 000 104 radim.

DESCRIPTION OF APPARATUS AND METHOD C.

In order to experiment on the radiation of air at various pressures, and to be able also to substitute other gases in the place of air, a closed vessel was needed. Of course this presupposes some sort of window transparent to the gaseous radiation, but both the window pane and the walls of the vessel visible through the window will contribute their own rays, and these must be capable of being certainly distinguished from those of the gas. This was effected by making the window pane of rock-salt and letting the opposite radiant wall be a movable one, formed of a blackened copper disk attached to a steel rod sliding in a stuffing box at one end of a large iron cylinder. By pushing the rod in and out, the length of the radiant air column could be changed without varying the temperature and radiant power of the solid parts. The disk served the further purpose of a stirrer, by the vigorous motion of which it was hoped that the temperature of the hot air could be made appreciably uniform. This hope was only partially realized, as the sequel will show; but, although it would be possible to devise a more efficient apparatus, the very errors of this one have proved instructive, and the final results, after the discussion and elimination of these errors, are believed to be trustworthy.

The radiation cylinder, as actually made, consists of an iron cylinder of 12 inches internal diameter, 60 inches long, weighing 250 pounds, with flanges at the ends projecting outward to a width of 2 inches. Heavy plates of cast iron are bolted to the flanges, the joints being luted with red rubber. The front end-plate, facing the bolometer, carries lugs and a ring-piece, with clamping screws by which a rubber-faced metal ring is held against a thick plate of rock-salt (thickness, 1.98 inches = 5.03 cm.; diameter, 3.80 inches = 9.65 cm.), holding it against a rubber ring surrounding the 2-inch aperture in the center of the end-plate. A glass plate slides over the outside of the salt, when not in use, to protect it from moisture. Preliminary experiments having proved that rock-salt might be heated to 175° C. and presumably much higher without danger of cracking, if it were shielded from currents of cold air and any sudden changes of temperature, but that without this precaution the salt was almost sure to crack, the circumference of the cylindrical block of salt was wrapped in about an inch of cotton wool. The large masses of metal (the end plates weigh about 20 pounds apiece) prevent any sudden cooling of the solid parts. The rear end-plate being pierced by a central aperture carries a stuffing box through which a half-inch rod of polished steel passes, air-tight, with rubber packing, its position and that of its terminal disk being read by divisions cut on the rod. The movable disk of blackened copper is 0.12 inch thick and 11.85 inches in diameter, leaving an annular opening with an average width of 0.075 inch through which the air rushes when the disk plays to and fro. A thermometer in the front part of the cylinder records the temperature of the air, and the disk is prevented from coming nearer than 4.25 inches (10.8 cm.) to the front plate by a fixed stop. This defines the shortest radiant air column which can be used, the longest being 60 inches (152.4 cm.).

The cylinder is heated from below by four large Bunsen burners, each having a protractor stopcock, reading to degrees, for the ready regulation of gas flow. An outer cylinder of sheet iron serves as a hot-air jacket to the inner one. Four openings below in the outer casing admit the flames, and the same number above permit the escape of combustion products.

An air pipe at the side connects the inner cylinder with air-pumps and a mercury gage, and a second air pipe leads to a small iron side-cylinder, or heater, provided with graduated stopcocks, and joined to a series of drying flasks, generators of carbon dioxide, etc., according to the needs of the experiment.

The apparatus is shown in plan on a scale of 1–12 in fig. 7.

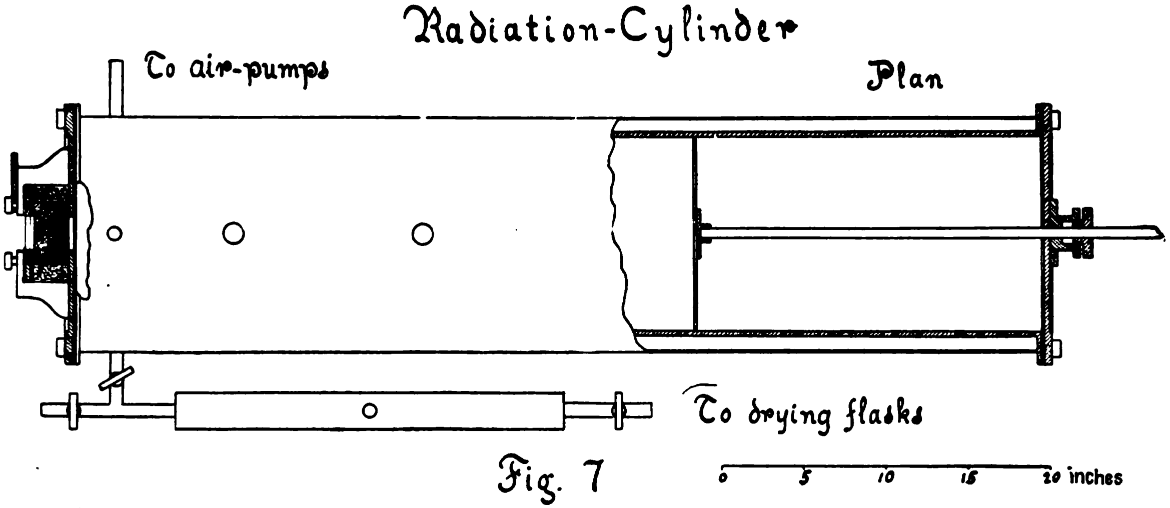

Fig. 7

The radiation cylinder has an approximate volume of 6,787 cubic inches = 111.3 liters, and holds about 144 grams of air at 760 mm. pressure and 0° C., containing, if unpurified, nearly 0.14

gram of carbon dioxide. The actual atmospheric pressure during the experiments was usually from 730 to 735 mm.

The bolometer is carried by a massive stand which permits accurate adjustment, and holds the instrument with a solidity which can not be improved. The mounting of the great cylinder in the first experiment was not so firm, but it was afterwards stiffened by braces and gave no further trouble. The entire apparatus stood on a stone pier.

The bolometer case was protected by the multiple tin-plate screens of small aperture, the outer screen being 2.46 in. from the front of the lead ring which clamps the rock-salt to the end-plate. In Jamin's "*Cours de physique*," 3^{e} ed., tome 3, 3^{e} fasc., p. 93, is an allusion to a source of error neglected in the otherwise very careful work of Melloni. The polished rock-salt plate reflects to the bolometer rays from a small annulus of the protecting screen, but the effect in my observations is very minute; first, because the polished tin plate does not absorb radiation well and is not much heated; second, because any rays which the screen may emit or reflect are only feebly reflected by polished rock-salt; third, because the angular aperture of the measuring instrument is small; and in general, since the gaseous radiation is measured by finding the change due to motion of an internal disk, the effect in question is constant at a given temperature, and without influence on the result.

GENERAL THEORY OF THE APPARATUS C.

When the disk in the heated apparatus is moved away from the bolometer, a deflection results which is made up (1) partly of positive gaseous radiation, (2) partly of diminished disk radiation due to greater gaseous absorption, (3) in part, of any change which takes place in rock-salt radiation, which may be either positive or negative, (4) of any change in the disk radiation due to its removal to a part of the cylinder having a different temperature. This also may be either positive or negative, and is quite appreciable if the cylinder is not uniformly heated, for instance, if one or more of the lamps are extinguished.

For the present purpose (2) need not be separated from (1). Absorption simply makes the gaseous radiation appear smaller. Considering (1) and (3), the rock-salt, if the supply of heat were equable, would tend to remain at a lower temperature, as a whole, than the gas within the cylinder, because the outer surface of the salt is cooled by contact with the outside air, and its entire substance radiates outwardly through a wide aperture. Nevertheless, since the thickness of the rock-salt plate is great, while its conductivity and radiative power are small, a very marked thermal gradient is produced within the salt, and in actual work its temperature is always changing. The air gets its heat chiefly by contact with the hot iron; the salt, on account of its small absorption of the radiation passing through it, gets its heat mainly by the air convection; and thus the temperature-changes of the salt continually lag behind those of the air and iron.* When the lamps are put out, the air and iron are at first hotter than the salt, but soon they become cooler than it. The withdrawal of the disk exposes the rock-salt to radiation from the walls of the cylinder, whose mean temperature may differ, and whose radiative power certainly differs from that of the disk, and also to contact with the gas swept over the face of the plate. If the gas is hotter than the plate, the salt is heated more rapidly than before by this increased contact with the air during the withdrawal of the disk, but also when it is pushed back. This part of the change is, therefore, eliminated in the same way that the effect of galvanometer drift is removed by combining readings made before and after exposure. The part of the rock-salt temperature-change due to variation of radiation during an observation is not thus eliminated, but is too small to be measured.

The variations in the radiation of the copper disk (and to a smaller extent those of the rock-salt) during an exposure by withdrawal of the disk, under certain extreme conditions, may equal or exceed the effect attributable to the combined radiation and absorption of the inclosed hot gas. Whether, therefore, there is any appreciable effect from the heated gas under the peculiar conditions of these experiments with the radiation cylinder might be uncertain were it not for the tests to be described.

---

* For further details in respect to rock-salt radiation, see the first part of my article on "The Probable Range of Temperature on the Moon," *Astrophysical Journal*, vol. 8, p. 199, Nov., 1898.

We can not suppose that changes in the thermal condition of the solid parts of the apparatus are ever entirely absent; but since the sign of these variations of temperature is reversed in passing from heating to cooling conditions, it might be supposed that a mean between deflections obtained with a heating cylinder and those from a cooling one would be due to gaseous radiation and absorption, the effect of any possible changes in the copper disk canceling out, and those of the rock-salt being eliminated by the mode of exposure, as already shown; but it will be seen subsequently that this interpretation of the results is not permissible, and that the effect of another cause of discrepancy—that of imperfect homogeneity of the gaseous radiating column—must be considered.

When the radiation cylinder is heating, the temperatures of the well-stirred air being taken as abscissæ, the observed radiations, plotted as ordinates, fall accurately upon a straight line, radiation being proportional to excess. With a cooling cylinder the radiations are very much smaller, and fall on a curved line. It would be very easy here, from an incomplete or an imperfectly analyzed experiment, to draw erroneous conclusions.

The wrought-iron cylinder (except where the flame plays directly upon it), by virtue of its thermal conductivity, must be not very far from the mean temperature of the hot-air jacket (which has been measured), but lagging behind somewhat both in heating and cooling. The temperature of the air within the cylinder lags still more, because of its small conductivity. The cylindrical surface of iron to be heated has an area of 2,263 square inches. The direct impact of the flame is exerted upon not more than $\frac{1}{100}$ of this surface, and the play of a flame at 1,000° to 1,800° C. heats this portion unduly, a considerable area of the floor of the radiation cylinder having, by conduction, more than the average temperature. Columns of hot air rise within the cylinder along its central axis during heating, over each of these hot places, and these columns, much hotter than the mean temperature of the air within the cylinder (which mean temperature is alone given by the thermometer), produce the larger deflections during heating. The supposition that change of temperature of the rock-salt has anything to do with the deflection has been shown to be untenable, and is most completely negatived when it is known that the total radiation of the salt is less than that represented by the deflection in question, while the temperature of rock-salt, and thence its radiation, changes very slowly. Variations of temperature in the copper disk in its two positions may produce considerable deflections, but only under extreme conditions which are not those of the actual experiment. Substitution of a blackened asbestos disk, a bad conductor of heat, in place of the conductive copper, also makes little difference in the result with a cooling cylinder, unless the temperature distribution is abnormal. The deflections obtained in the ordinary working can, therefore, only be due to the changing dimensions and temperatures of the hot-air columns within the cylinder; and the fact that there is a larger radiation at a given mean temperature, as indicated by the thermometer, when the temperature of the cylinder is increasing, together with the observed relation between the rapidity of the heating and the amount of the radiative excess over the measurement with a cooling cylinder, the deviation being greater the more rapid the heating, testify that the radiation comes from a body subject to the internal changes and irregular structure produced by convection; and an effect which at first sight may seem anomalous becomes a proof that the radiation observed is really that of the air, and is not due to any change in the thermal condition of the solid parts of the apparatus during exposure. In passing from the condition of a heating cylinder to that of a cooling one, with but slight change of average temperature, there is a continuous fall of radiation, that for the stationary point being less than for increasing temperature, but more than for falling temperature.

When heated from below, the central region of an inclosed fluid is occupied by ascending columns heated beyond the mean temperature of the mass, while during cooling the central currents are cooler than the average. This central region in the present case is the only one observed by means of the bolometer whose indications do not give the average radiation of all the air in the cylinder, but that of the rapidly moving and thermally varying portion included within the central cone of rays.

The composition of the axial radiating air column when heating may be analyzed, probably with some approximation to the truth, as follows: Suppose that nine-tenths of the air in the horizontal stretch of this axial line have a temperature of 90° and radiate with an intensity of

4 for each tenth, or 36 in all, while one-tenth is air just rising by convection and heated to 250° by contact with the hot iron. The radiative power of this tenth may be taken as 85, and the total radiation is 121; whereas the radiation of a body of air at mean temperature

$$\frac{(9 \times 90) + 250}{10} = 106^\circ$$

will be about 68 on the same scale, and the observed radiation is nearly double that appertaining to the given mean temperature.

When the disk is "in"—*i. e.*, at its nearest approach to the rock-salt plate, while the temperature is increasing, the thermometer of the radiation cylinder is partially separated from the larger part of the interior space and from the chief source of heat supply. The reading of the thermometer is therefore lower, since the ends of the cylinder cool faster. But even with the disk out, the thermometer reading is too low, as is shown by a rise of several degrees after a quick movement of the disk to and fro several times when the heating cylinder has not been recently stirred. After about ten minutes of cooling, however, with less frequent agitation, no change in the thermometer reading occurs after stirring. The distribution of temperature is therefore more equable during cooling. The thermometer, after vigorous stirring of the air, records its true temperature, as in the use of the sling thermometer.

In order to get the thermometer out of the line of radiation, it had to be lifted a little above the central axis of the cylinder. Hence, without mixture of the air layers, the reading should have been too low in heating, too high in cooling. (See thermal diagrams.) The last error, however, is inappreciable, and I think we may see why from the following considerations: When heating, the metal at the bottom of the cylinder is quite hot; that at the top much cooler. The air is heated by contact at the bottom, and being thus lighter and in unstable equilibrium, it rises and carries heat to the middle space, mixing with cooler air until its ascension is stopped by the top wall, and great diversity of temperature prevails. For example, internal air in immediate contact with the iron top and bottom walls being at 50° and 250°, respectively, an air temperature of 90° should be found at some point in the upper half of the air space when the mean temperature of the entire mass of air is 110°, ascending thirds of the air being on the average 150°, 100°, 80°. Stirring may then cause a rise of 20°, as has actually occurred, and streaks of air as hot as 200° may reach the central line, contributing more than their share to the total radiation on account of their relatively greater radiative power.

The following centigrade temperatures of the hot-air jacket of the radiating cylinder were observed (temperature rising):

		°
Jacket:	At the top, near center	257
	" " " " end	250
	" " side " "	140
	" " bottom " "	56

$$\left.\begin{array}{l} \text{Upper half, } \dfrac{254 + 140}{2} = 197^\circ \\ \text{Lower half, } \dfrac{140 + 56}{2} = 98 \end{array}\right\} \text{Mean} = 148$$

Temperature of air within the radiation cylinder = 110°.

A hypothetical vertical thermal section of the air in the cylinder is indicated in the diagram:

	°
Top wall of cylinder	50
Internal air	$90^\circ \left\{\begin{matrix} 80 \\ 100 \\ 150 \end{matrix}\right\} 110^\circ$
Bottom wall	250

The cooling of the metal after the lamps are extinguished is chiefly from beneath by convection currents, which rush upward through the space between the radiation cylinder and the outer jacket, while the air within the cylinder is cooled by contact with the metal at the top, whose temperature differs less than before from the bottom temperature, and little change is suffered by the air from contact with the cooler metal at the bottom on account of the feeble conductivity of air and stagnation by greater density there. Thus the distribution of temperature in cooling may be this: Air in immediate contact with iron, 110° and 75° at top and bottom, respectively. Air temperature by ascending thirds: 105°, 110°, 115°. Mean, as before, 110°.

The following temperatures of the hot-air jacket were observed after the preceding ones, but with a cooling cylinder, all of the lamps but one (the second from the rock-salt) having been extinguished:

		°
Jacket·	At the top, near center	129
	" " " " end	117
	" " side " "	95
	" " bottom " "	56

$$\left.\begin{array}{l}\text{Upper half, } \dfrac{123+95}{2} = 109^{\circ} \\[2ex] \text{Lower half, } \dfrac{95+56}{2} = 75.5\end{array}\right\}\text{Mean} = 92$$

Internal temperature of radiation cylinder = 110°.

A hypothetical internal vertical temperature distribution in close agreement with these observations is shown in the diagram:

Top wall of cylinder		110°	
Internal air	112°.5 {	115 110 105	} 110°
Bottom wall		75	

Here all layers of air have nearly the same temperature. The position of the internal thermometer is of little consequence, and small change results from stirring.

Curves of radiation and temperature with a cooling cylinder pass so nearly through the points of observation after prolonged stationary temperature that no great error will be committed by assuming the cooling observations to be correct after cooling has progressed for a little time.

That the larger radiations during rapid heating are abnormal, and indicate excessive heating of the bottom of the cylinder and of the lowest layers of gas, is proved by the fact that under these circumstances the apparent mean temperature of the gas, on putting out the lamps, does not vary much during many successive stirrings, although the deflections diminish continually until the customary reading corresponding to that temperature and uniform distribution of heat is reached, after which the thermometer begins to fall rapidly and the radiation to diminish according to the usual law.

Example: Cylinder containing carbon dioxide. After heating for several hours the lamps were put out and readings taken during initial cooling. Battery galvanometer, 113 div., but here all deflections have been reduced to standard current. Each deflection in this and the following experiments, unless otherwise specified, is the mean of five concordant readings.

All temperature-excesses are reckoned from the temperature of the bolometer, there being no other standard possible in the mode of exposure followed, and are given in centigrade degrees. Pressure in closed cylinder varying from 744 mm. to 718 mm., mean 731 mm. (reduced to freezing point). Temperature of room, 30°.2; of bolometer, 35°.2; dew-point, 13°.9 C.

TABLE 26.

Heating rate per minute.		Temperature.	Excess.	Radiation.
	°	°	°	*Divisions.*
Series 1:	+0.83	132.6	97.4	+19.2 (abnormal)
Lamps out		133.2 Max.	98.0	
After 3 min.	—0.13	133.0	97.8	+15.7 "
" 7 "	—0.73	131.4	96.2	+12.4 "
" 12 "	—1.10	125.5	90.3	+ 8.7 (normal)
Series 2 (after further heating)	± 0	127.4	92.2	+16.5 (abnormal)
Lamps out		136.2 Max.	101.0	
After 5 min. cooling	—0.36	135.3	100.1	+14.5 "
" 10 " "	—1.23	126.9	91.7	+ 9.5 (normal)

The last and subsequent readings of each series are normal, the temperature, as indicated by the internal thermometer, diminishing rapidly.

A similar result has been obtained in the use of an asbestos disk, but here other causes assisted. To determine what change, if any, would take place if the radiative disk were nonconducting, the copper had been covered with blackened asbestos on the side facing the rock-salt window. With a heating cylinder the *apparent* air radiation was greater when the nonconducting disk was used, and much greater when only the two central lamps were lighted and the ends of the cylinder were at lower temperatures than under normal conditions, even although the duration of the experiment was prolonged until a stationary mean temperature was reached. The surface chilling of the disk in the forward position—*i. e.*, nearest to the rock-salt, increased the deflection, and the effect persisted until the difference of temperature between the middle and the ends of the cylinder ceased. The abnormal results at maximum temperature and during initial cooling, while the apparent or recorded mean temperature is nearly stationary, are in this case due to the combined effect of vertical and horizontal inequality of temperature.

Example: Cylinder filled with air at atmospheric pressure, thoroughly dried by phosphoric anhydride, and purified from carbon dioxide. After heating continuously for 23 hours the recorded mean stationary temperature was 68°.9. The two middle lamps were then turned up for 1 minute, until the temperature had risen to 71°, when the lamps were extinguished.

TABLE 27.

Heating rate per minute.		Temperature.	Excess.	Radiation.
	°	°	°	*Divisions.*
	+2.1	70.0	38.0	+8.0 (abnormal)
Lamps out		71.0 max.	39.0	
After 4 min. cooling	±0.0	71.0	39.0	+7.5 "
" 8 " "	±0.0	71.0	39.0	+5.8 "
" 12 " "	—0.12	70.8	38.8	+4.6 "
" 16 " "	—0.28	70.0	38.0	+3.9 "
" 20 " "	—0.10	69.2	37.2	+2.8 (normal)

Here, after prolonged but unequal heating, 20 minutes of cooling were required to give the approximation to a normal value, recorded in the last line, the first reading being nearly three times too large.

The preceding example was obtained after all parts of the cylinder had become well heated, the inequalities of thermal distribution being comparatively small. The next experiments show the extraordinary increments produced by the use of the asbestos disk with a rapidly heating cylinder. The air within the cylinder was approximately dry, and purified from carbon dioxide. Two middle burners were lighted, with cocks set at 30 div.

TABLE 28.

Heating rate per minute.	Temperature.	Excess.	Radiation.
°	°	°	*Divisions.*
+1.2	62.4	25.8	+ 8.4
+1.4	72.5	35.9	+16.2
+1.8	80.3	43.7	+20.9
+2.1	90.0	53.4	+24.6
+2.6	100.3	63.7	+30.6
+2.0	108.9	72.3	+35.5

The deflections are here four to six times as great as those with a cooling cylinder. A repetition of the experiment gave the results in Table 29.

TABLE 29.

Heating rate per minute.	Temperature.	Excess.	Radiation.
°	°	°	*Divisions.*
+3.6	61.8	28.2	+13.4
+2.4	70.8	37.2	+17.3
+4.0	81.0	47.4	+25.0
+4.2	90.9	57.3	+26.1
+2.8	100.2	66.6	+32.6
+2.0	110.2	76.6	+37.7

The observations may be represented by a straight line passing through the origin and a deflection of 30 div. at excess 63°, giving a mean deflection of 0.476 div. per degree of excess. The ratios to the deflections of the cooling curve are, as before, about six to one at the middle of the heating curve, where the rate of heating is greatest.

The asbestos in the forward position radiates to the cooler iron of the end-plate, and hence becomes cooler. When withdrawn to the rear the blackened surface of the asbestos absorbs radiation from the hot interior, and is also heated by contact with hotter gas; but, although the copper back is now near a cooler end-plate, the nonconductivity of asbestos prevents any influence from this cause. The positive differential effect is added to the true gaseous radiation. The conductivity of copper, and the more equable distribution of temperature in the metal walls, prevent any but a small temperature-change in the copper disk during the time of an observation in the normal working of the heating cylinder, and the larger deflections with heating cylinder are in this case due almost entirely to inequality of gaseous temperature, as is shown by the closer agreement of the readings, after prolonged heating to a stationary temperature, with those of the cooling curve; but the results with asbestos, under the same circumstances, are different. When the lamps are put out, the distribution of temperature in the cooling iron, after a time, becomes nearly uniform, the increase of 200 or 300 per cent. in the apparent gaseous radiation with stationary mean temperature, due really to temporary chilling and heating of the surface of the blackened asbestos, then ceases, and the values of air radiation, observed with a cooling cylinder, are nearly the same with an asbestos disk as with copper. These measures may therefore be included with those from which the final curves of air radiation are derived. The abnormal values which have been purposely obtained by varying the method and conditions of working, are only used to arrive at an understanding of the meaning of the ordinary results, and to derive some indication as to their reliability. Many things which were puzzling at the time the experiments were made are now clear to me, and I hope that they will be so to the reader who has the patience to follow the details of a research beset with difficulties and intricacies.

The following experiment with the blackened copper disk exhibits the result of a still wider departure from normal conditions, and bears witness to the necessity of some of the precautions which were taken in the ordinary use of the apparatus. In heating the hot-air jacket around the radiation cylinder, four large Bunsen burners are customarily employed, their positions being such as to secure as uniform distribution of temperature as possible within the cylinder with the given means. With only one lamp lighted, the effects are very different, according to the position of the lamp. When the single lamp was at the end farthest from the rock-salt, there was a positive deflection. The mean temperature of the inclosed air had been so regulated that it was falling, a condition ordinarily attended by smaller galvanometer readings. On the other hand, when the single lamp was at the rock-salt end, the deflection became negative with a heating cylinder, which ordinarily gives increased readings.

The observation follows: Battery current, standard, or 100 div. Temperature of room, 26°; of bolometer, 31°; dew-point, 11°.7, corresponding to a pressure of aqueous vapor of 10.23 mm. or 10.28 grams per cubic meter, and to an equivalent liquid depth of 0.000 387 cm. in the absorbent layer.

(*a*) Fourth lamp (farthest from the rock-salt) lighted. Burner cock set at 30 div. Temperature of air in cylinder read immediately after vigorous stirring:

	°
Temperature before experiment	102.2
" after "	97.8
mean =	100.0
Excess =	69.0

Cooling rate, 0°.88 per minute; mean differential radiation (disk shifted from 0.35 to 5.0 feet) = + 7.80 div.

(*b*) First lamp (nearest to rock-salt) lighted. Burner cock set at 35 div. The other lamp put out.

	°
Temperature before experiment,	104.6
Temperature after experiment,	108.0
Mean, =	106.3
Excess, =	75.3

Heating rate, 0°.68 per minute. Mean differential radiation (disk shifted as before) = − 1.34 div.

Analyzing the component sources of radiation in these two experiments, and neglecting absorption, it will be seen that in (*a*) the copper disk was getting hotter when "out," and was cooling when "in," or at the end next to the rock-salt. Its thermal change had the same sign as the hot-air radiation during exposure of the air column. The front walls of the cylinder were cooler than the rear walls, and cooler than the copper disk, since the latter evidently suffered not merely a halt in its thermal increment, when at the front, but a decided decrement of heat. Changes in the temperature of the rock-salt contributed to the combined effect, although only to a slight degree, since the radiating power of the rock-salt plate was but one-fourth that of blackened copper at the same temperature, and its rate of change very slow. When the warm copper disk was pulled out, the salt received radiation from the front walls of the iron cylinder, far from the flame, and certainly cooler than the frequently heated copper, also less powerfully emissive. At the same time, cooler descending internal convection currents played upon the salt, cooling it, while the disk was getting hotter. The thermal change of the salt was, therefore, opposite to that of the copper.

In experiment (*b*) the copper disk was heated at the front and was cooling while at the farther end. Its change of radiation was therefore of the opposite sign to the always positive radiation of the column of heated air (disk out), and since the rock-salt (disk out) was exposed to the radiation of neighboring walls hotter than the disk, and also to the warmer internal convection currents which then ascended at the front, the thermal change of the salt again had the opposite sign to that of the disk.

If δc = the variation of radiation dependent upon thermal change in the black copper in the time of exposure,

δs = the corresponding variation depending upon thermal change in the rock-salt, modified by its own absorption,

r = the mean radiation of the hot air, as affected by self-absorption and assumed to be constant,

x = the transmission of hot air radiation by salt,

y = the transmission of the radiation of black copper by hot air and salt,

z = the transmission of the composite radiant beam issuing from the rock-salt, exercised by the air between the salt and the bolometer,

we may express the facts of these experiments thus:

$$(a)\qquad z\,(xr + y\delta c - \delta s) = +\,7.80$$
$$(b)\qquad z\,(xr - y\delta c + \delta s) = -\,1.34$$

The change of radiation of the rock-salt in a quiescent atmosphere has been found quite inappreciable during the time of exposure, and, although somewhat larger under strong convection currents, it is still a very small quantity; but for illustration it may be included, taking $\delta s = \frac{1}{50}\,y\delta c$. The equations give

Constant radiation of hot air	$xzr = +\,3.23$
Variation due to thermal change in copper	$yz\delta c = \pm\,4.66$
Variation due to thermal change in salt	$z\delta s = \pm\,0.09$

The total radiation of black copper, rock-salt, and air on this occasion was found to be 52.3 div., the excess being 74°. This radiation is made up approximately of—

Radiation of black copper, transmitted by salt	39.3
Radiation of air, transmitted by salt	3.2
Radiation of rock-salt	9.8

The rock-salt plate having absorbed one-fourth of the original radiation from the interior, the initial deflections before absorption may have been:

Blackened copper	$39.3 + 13.1 = 52.4$
Air	$3.2 + 1.1 = 4.3$

The indicated radiation for the blackened copper is not far from normal, but the air radiation is only a little over one-third of that obtained by the usual method, no doubt because, with but one lamp burning, only a part of the air is effective, the distribution of temperature being far from uniform, as the variation in the temperature of the copper disk at opposite ends of the cylinder also proves.

The influence of self-absorption of its own radiations by a gas brings into play another factor which changes with the depth of the gaseous layer. By varying the play of the disk in exposure, this feature may be partly determined, but its complete elucidation demands apparatus with a great range of dimensions.

Paschen ("Ueber die Emission der Gase," *Wied. Ann.*, Bd. 51, S. 30, 1894) finds that a 7-cm. layer of carbon dioxide absorbs at the position of its chief band "like an infinitely thick layer," and that the absorption of aqueous vapor is by no means proportional to the depth, but increases (at wave length 2.60μ) from 60 per cent. to 80 per cent., when the depth of the vaporous layer varies from 7 cm. to 33 cm. (*loc. cit.*, p. 12). Hence, gaseous radiant emission is not proportional to the depth, except for small depths, and it is conceivable that there may be, for a given depth, some temperature of the gas at which there is such a compensation of emission by absorption that increase of thickness will not affect the quantity—disk radiation plus gaseous radiation plus gaseous absorption. In fact, Paschen's fig. 8 (Taf. 1, *Wied. Ann.*, Bd. 51) shows that the ratio of gaseous emission to gaseous absorption for carbon dioxide changes with the temperature, and the same figure permits a determination of one point on a curve of compensation of radiation by absorption for this gas.

The first measurements made with apparatus C were to find the relation between air radiation and depth, and to these we may now pass.

METHOD C.—EXPERIMENTS IN WHICH THE DEPTH AND PRESSURE OF THE AIR HAVE BEEN VARIED.

Each of the two air-pumps diminished the pressure in the cylinder by about 100 mm. with the first 20 strokes; but owing to the slow action of the valves, it was difficult to get the final pressure below 50 mm., although the pumps worked well enough when the receiver to be exhausted was small. In addition to this trouble, there has always been some leakage at low pressures—*e. g.*, in one experiment where the air temperature did not exceed 100° C., the gage at $4^h\ 27^m$ read 94.6; at $5^h\ 32^m$ the reading was 98.4 mm., the pressure having risen 3.8 mm. in 65^m, or 0.059 mm. per minute, and fresh leaks have frequently started from the strain of heating. Consequently, in experiments with partial vacuum, it has been necessary to work rapidly, and in spite of drying flasks, some aqueous vapor must enter through leakage. The final method which overcame this difficulty was the introduction of a bowl of phosphoric anhydride within the cylinder. After repeated exhaustions, allowing air to flow into the cylinder through a series of flasks containing porous chloride of calcium, experiments were commenced January 25, 1893, with air nearly dry, but still containing carbon dioxide in the usual small proportion. Without further announcement, it may be understood that in all the readings which follow, the deflections have been reduced to standard conditions of current and bridge. The change is usually very small, but in the present case, with battery galvanometer 95 div., the arrangement of the bridge was insensitive, and the multiplier is 2.0. Mean temperature of room, 20°; of bolometer, 25°; dew-point, 12°.2. Pressure of aqueous vapor, 10.57 mm., or 10.71 grams per cubic meter. The absorbent layer contained enough water to make a liquid depth of 0.000 403 cm. The disk was set at even feet, but the initial reading with which comparison is to be made is that of the shortest air column, 0.35 feet. The measurements were made at both ordinary and low pressures.

TABLE 30.

Position of disk, feet.		0.35.	1.	2.	3.	4.	5.	Temperature.	Excess.	Pressure.
Air depth	ft.	0	0.65	1.65	2.65	3.65	4.65			
	cm.	0	19.8	50.3	80.8	111.3	141.8			
			div.	*div.*	*div.*	*div.*	*div.*			
Deflections		0	4.8	15.0	23.2	35.4	33.6	170°	145°	95^{mm}.
		0	6.0	15.8	24.0	32.6	32.0	185.5	160.5	723
Mean deflection		0	5.4	15.4	23.6	34.0	32.8			
Change per foot		....	8.3	10.0	8.2	10.4	—1.2			

The two series in this table, taken at pressures which vary in the ratio of 1: 7.6, are almost identical. The discussion of this at first sight rather startling fact is reserved for a subsequent section. Except for the last foot the increase of radiation is proportional to the depth. In view of what has been said as to the effect of unequal distribution of temperature it might be suspected that the diminished deflection at the fifth foot comes from the chilling of the disk by proximity with the cooler end-plate, but this is not the true explanation, as the next example demonstrates.

TABLE 31.

Cylinder filled with dry carbon dioxide.

Position, feet.		0.35	1.	2.	3.	4.	5.	Temperature.	Excess.	Pressure.
Depth	ft.	0	0.65	1.65	2.65	3.65	4.65			
	cm.	0	19.8	50.3	80.8	111.3	141.8			
Mean deflection (div.)		0	3.5	7.6	10.4	10.5	10.2	142°.7	125°.8	766^{mm}.
Change per foot		....	5.4	4.1	2.8	0.1	—0.3			

Two things are shown clearly by these concise tables, namely, that, allowing for the difference of temperature, the apparent radiation of carbon dioxide is smaller than that of dry air at temperatures not exceeding 200° C. and that the law of increase of radiation with the depth is entirely different for these two substances. To make the last point quite certain, the experiment was repeated with dry carbon dioxide, first at atmospheric pressure and then at low pressure. These measures are given in full as an example of the mode of observation.

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Each complete observation consists of three successive series, of ten readings each, with differential depths of carbon dioxide gas of 4.65 feet, 1.65 feet, and again 4.65 feet, the middle series being contrasted with the mean of the extremes to eliminate the variation from change of temperature. Each deflection is from three galvanometer readings, with disk in, out, and in again, and is complete in itself.

Battery galvanometer, 100 div. Barometer, 734 mm., which is the pressure of the gas in the first three series. Temperature of the bolometer, assumed to be 5° hotter than the reading of the dry-bulb thermometer placed beside the bolometer case. The temperature of the bolometer is taken as the initial or comparison temperature.

At $11^{h}\ 9^{m}$, dry bulb = 63°.8 F. = 17°.7 C.
wet bulb = 55°.1 F. = 12°.8 C.

Difference, 8.7 + 4.4 (correction for unventilated psychrometer of 50 per cent.) = 13°.1 F. Dew-point, 38° F. Relative humidity, 0.38. Temperature of radiation cylinder = 121°.0 C.

TABLE 32.

(Series 1.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	5.0	0.35		
				div.
105.1	113.0	104.1	104.6	+8.4
104.1	112.0	105.2	104.7	+7.3
106.1	113.3	103.4	104.8	+8.5
105.0	112.6	108.0	106.5	+6.1
100.0	109.5	103.0	101.5	+8.0
103.0	114.2	105.8	104.4	+9.8
106.1	114.2	105.8	106.0	+8.2
103.0	112.1	102.5	102.8	+9.3
102.5	111.4	103.0	102.8	+8.6
103.0	112.2	104.0	103.5	+8.7
Differential radiation for depth (4.65 ft.).				+8.29

At $11^{h}\ 19^{m}$, dry bulb = 65°.0 F. = 18°.3 C.
wet " = 56°.0 F. = 13°.3 C.
Difference = 9.0 + 4.5 (correction) = 13°.5 F.
Dew-point, 38° F. Relative humidity, 0.37.
Temperature of radiation cylinder = 126°.8 C.
Mean temperature of radiation cylinder (series 1) = 123°.9 C.
" " " excess (series 1) = 100°.9 C.

Mean dew-point, 38° F. = 3°.3 C., or pressure of aqueous vapor = 5.78 mm., corresponding to 6.04 grams of water per cubic meter of air, and to an equivalent depth of liquid water of 0.000 227 cm. in the absorbent air layer. At $11^{h}\ 25^{m}$, temperature of radiation cylinder = 133°.0 C.

TABLE 33.

(Series 2.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	2.0	0.35		
				div.
100.0	109.1	103.8	101.9	+7.2
99.2	107.7	100.8	100.0	+7.7
100.8	109.6	103.8	102.3	+7.3
102.7	111.1	105.5	104.1	+7.0
105.5	114.0	107.0	106.3	+7.7
102.0	112.0	105.7	103.9	+8.1
105.9	112.8	108.0	107.0	+5.8
97.8	105.0	98.2	98.0	+7.0
98.2	108.1	102.6	100.4	+7.7
102.6	111.0	101.9	102.3	+8.7
Differential radiation for depth (1.65 ft.).				+7.42

At $11^h\ 33^m$, dry bulb = $65^\circ.9$ F. = $18^\circ.8$ C.
wet " = $57^\circ.0$ F. = $13^\circ.9$ C.
Difference = 8.9 + 4.5 (correction) = $13^\circ.4$ F.
Dew-point, 40° F. Relative humidity, 0.38.
Temperature of radiation cylinder = $143^\circ.2$ C.
Mean temperature of radiation cylinder (series 2) = $138^\circ.1$ C.
" " " excess " = $114^\circ.5$ C.

Mean dew-point, 39° F. = 3.9° C., or pressure of aqueous vapor = 6.03 mm., corresponding to 6.23 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 234 cm. in the absorbent air layer.

TABLE 34.

(Series 3.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	5.0	0.35		
				div.
105.3	116.8	105.0	105.2	+11.6
105.0	120.0	106.8	105.9	+14.1
106.0	118.2	107.1	106.6	+11.6
107.1	119.0	109.0	108.1	+10.9
101.6	112.3	101.0	101.3	+11.0
101.0	112.0	101.8	101.4	+10.6
101.8	112.9	102.0	101.9	+11.0
102.0	115.0	101.8	101.9	+13.1
103.0	116.0	102.8	102.9	+13.1
102.8	115.0	103.7	103.3	+11.7
Differential radiation for depth (4.65 ft.).				+11.87

At 11^h 43^m, dry bulb = 66°.8 F. = 19°.3 C.
wet " = 57°.4 F. = 14°.1 C.
Difference = 9.4 + 4.7 (correction) = 14°.1 F.
Dew-point, 40° F. Relative humidity, 0.37.
Temperature of radiation cylinder = 146°.7 C.
Mean temperature of radiation cylinder (series 3) = 145°.0 C.
" " " excess " = 120°.9 C.

Mean dew-point, 40° F. = 4°.4 C., or pressure of aqueous vapor = 6.24 mm., corresponding to 6.50 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 244 cm. in the absorbent layer of air.

The cylinder was now partially exhausted for the low-pressure experiments.

At 12^h 6^m, dry bulb = 68°.0 F. = 20°.0 C.
wet " = 59°.0 F. = 15°.0 C.
Difference = 9.0 + 4.5 (correction) = 13°.5 F.
Dew-point, 43° F. Relative humidity, 0.40.
Temperature of radiation cylinder = 149°.9 C.
Pressure in " " = 85 mm.

TABLE 35.

(Series 4.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	5.0	0.35		
				div.
93.8	105.0	93.2	93.5	+11.5
93.2	105.1	90.7	92.0	+13.1
90.7	103.2	91.5	91.1	+12.1
91.5	103.5	92.2	91.9	+11.6
92.2	105.0	92.0	92.1	+12.9
92.0	102.0	91.2	91.6	+10.4
91.2	104.1	88.0	89.6	+14.5
88.6	102.1	87.4	88.0	+14.1
87.4	101.1	86.8	87.1	+14.0
86.8	99.4	86.1	86.5	+12.9
Differential radiation for depth (4.65 ft.).				+12.71

At 12^h 12^m, dry bulb = 68°.8 F. = 20°.4 C.
wet " = 59°.8 F. = 15°.4 C.
Difference = 9.0 + 4.5 (correction) = 13°.5 F.
Dew-point, 45° F. Relative humidity, 0.41.
Temperature of radiation cylinder = 154°.0 C.
Mean temperature of radiation cylinder (series 4) = 152°.0 C.
" " " excess (series 4) = 126°.8 C.

Mean dew-point, 44° F. = 6°.7 C., or pressure of aqueous vapor = 7.31 mm., corresponding to 7.55 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 284 cm. in the absorbent layer of air.

Pressure of carbon dioxide, 85 mm.

TABLE 36.

(Series 5.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	2.0	0.35		
				div.
99.0	109.6	100.2	99.6	+10.0
103.3	112.9	101.9	102.6	+10.3
101.9	114.0	103.9	102.9	+11.1
97.2	108.4	97.0	97.1	+11.3
100.2	108.5	99.6	99.9	+ 8.6
100.0	111.4	101.8	100.9	+10.5
101.8	112.2	104.4	103.1	+ 9.1
99.0	109.8	100.2	99.6	+10.2
100.2	109.2	101.3	100.8	+ 8.4
100.5	111.1	103.2	101.9	+ 9.2
Differential radiation for depth (1.65 ft.).				+ 9.87

At 12^h 19^m, dry bulb = 69°.1 F. = 20°.6 C.
wet bulb = 58°.6 F. = 14°.8 C.
Difference = 10.5 + 5.3 (correction) = 15°.8 F.
Dew-point, 38° F. Relative humidity, 0.32.
Temperature of radiation cylinder = 163°.8 C.
Mean temperature of radiation cylinder (series 5) = 158°.9 C.
" " " excess (series 5) = 133°.4 C.

Mean dew-point, 41°.5 F. = 5°.3 C., or pressure of aqueous vapor = 6.64 mm., corresponding to 6.90 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 259 cm in the absorbent layer of air.

Pressure of carbon dioxide = 91 mm.
Mean pressure of carbon dioxide (series 5) = 88 mm.

TABLE 37.

(Series 6.)

Position of disk.			Mean in.	Deflection.
In.	Out.	In.		
Depth of gas (feet).				
0.35	5.0	0.35		
				div.
103.0	113.0	99.3	101.2	+11.8
99.3	112.3	99.3	99.3	+13.0
99.3	111.0	97.3	98.3	+12.7
97.3	111.2	94.9	96.1	+15.1
94.9	108.2	95.0	95.0	+13.2
95.0	107.6	94.0	94.5	+13.1
94.0	110.0	94.1	94.1	+15.9
94.1	108.9	92.5	93.3	+15.6
92.5	108.8	93.0	92.8	+16.0
93.0	107.2	92.0	92.5	+14.7
Differential radiation for depth (4.65 ft).				+14.11

At $12^h\ 26^m$, dry bulb = 69°.8 F. = 21°.0 C.
wet bulb = 60°.2 F. = 15°.7 C.
Difference = 9.6 + 4.8 (correction) = 14°.4 F.
Dew-point, 43° F. Relative humidity, 0.38.
Temperature of radiation cylinder = 164°.8 C.
Mean temperature of radiation cylinder (series 6) = 164°.3 C.
" " " excess (series 6) = 138°.5 C.

Mean dew-point 40°.5 F. = 4°.7 C., or pressure of aqueous vapor = 6.37 mm., corresponding to 6.63 grams per cubic meter of air, and to an equivalent depth of liquid water of 0.000 249 cm. in the absorbent layer of air.

Pressure of carbon dioxide = 96 mm.
Mean pressure of carbon dioxide (series 6) = 93.5 mm.

TABLE 38.—*Summary.*

Series.	Air layer.		Carbon dioxide in radiation cylinder.					
	Pressure.	Water cm. × 10^{-6}	Temperature.	Excess.	Pressure.	Radiation.		Ratio δ 4.65 + δ 1.65
						δ 4.65 ft.	δ 1.65 ft.	
	mm.		°	°	*mm.*	*dir.*	*dir.*	
1	734	227	123.9	100.9	734	8.29		
2	734	234	138.1	114.5	734		7.42	$\frac{10.08}{7.42}$ = 1.358
3	734	244	145.0	120.9	734	11.87		
4	734	284	152.0	126.8	85	12.71		
5	734	259	158.9	133.4	88		9.87	$\frac{13.41}{9.87}$ = 1.359
6	734	249	164.3	138.5	93.5	14.11		

As in the case of air, there is scarcely any difference in the radiation which can be attributed to change of pressure. The change of radiation with the depth is also unaffected by pressure. When the depth is increased in the ratio $\frac{4.65}{1.65} = 2.818$, the differential deflection is only increased in the ratio 1:1.359. Table 31 gives for the same depths the ratio of deflections $\frac{10.2}{7.6} = 1.342$, and the results of Table 31 for the 2d and 5th feet are confirmed by the more elaborate measures of Table 38.

Professor Paschen ("Emission erhitzer Gase," *Wied. Ann.*, Bd. 50, Taf. 9, fig. 9, 1893) gives a series of spectral energy-curves for the principal maximum of carbon dioxide at temperatures 110°, 158°, 330°, 622°, 710°, and 973° C., the radiation proceeding from a layer of the heated gas about 3 mm. deep. At the lowest temperature, which is a little below the highest in my observations, the deflections are very small, and the spectral energy-curve is very flat, but is still shown as a distinctly limited emission-band whose extreme wave-lengths do not differ by more than a fraction of a micron. Measuring the areas of the first four curves of Paschen's figure, the relative radiations are found to be—

Temperature	110°	158°	330°	622°
Radiation*	75	227	1,630	4,905

Drawing a curve through these values, and also (anticipating a little) one to represent my final measures of the total apparent radiant emission, the depths of radiant gas being 3 mm. and

---

* Measured in arbitrary units.

1,418 mm., the following approximate relative radiations for moderate temperature-excesses have been read from the curves:

TABLE 39.

Depth.	$t=20°$	$t=40°$	$t=60°$	$t=80°$	$t=100°$	$t=120°$
cm.						
0.3	1	4	12	30	59	100
141.8	2	7	17	36	65	100

The rate of increase of radiation with that of temperature is greater for a 3-mm. layer than for one of 1,418 mm., because the absorption in the mass of great depth partly neutralizes its own radiation. This is proved by the preceding experiments, which have demonstrated that a 5-foot layer of carbon dioxide radiates but little more than a 2-foot layer, and no more than a 3-foot layer. The rate of increase of radiation with temperature for a 5-foot layer of air does not differ much from the corresponding rate for carbon dioxide at these low temperatures, and the absolute radiations also are not very different; but, unlike carbon dioxide, the air radiates in proportion to the depth. It may be that this is because the measured radiation of air in my final experiments has been to a considerable extent that of its oxygen, nitrogen, or argon, and not merely that of the more highly absorbent and at high temperatures more powerfully radiant carbon dioxide or water-vapor. Since, at high temperatures and in thin layers, the radiative power of these strong absorbents is immensely greater than that of air, it follows that the rate of radiant increase with the depth for air at higher temperatures must be very much slower than for carbon dioxide, and that at particular depths and temperatures, which have been reached in the present research, the total radiations of these substances are more nearly equal. It is not possible, however, that equable increase of air radiation with depth can continue indefinitely, since the heat lost by layers of such dimensions as we have in the atmosphere, and imparted by radiation from the atmosphere to the earth, would have to be much greater, in that case, than it actually is.

The differential deflections in Tables 30 and 31 may best be compared by stating them as percentages of the deflection with disk at 4 feet.

TABLE 40.

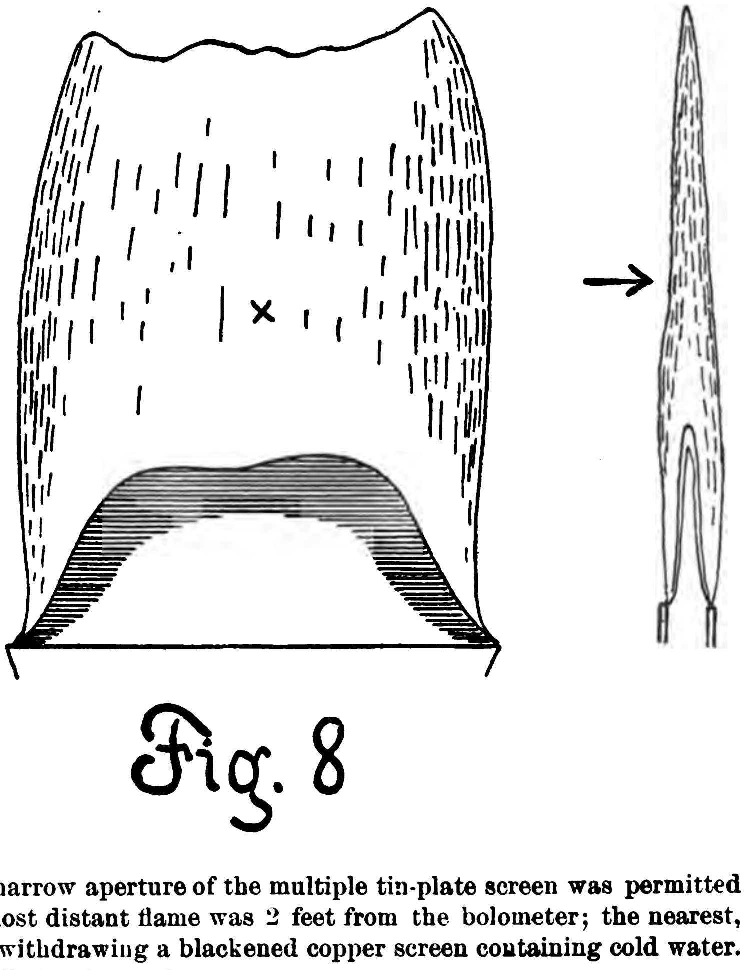
Position of disk.	Depth of gas.	Air at 185°.5 and 723 mm.	CO_2 at 125°.8 and 766 mm.	Increase per foot.	
				Air.	CO_2.
Feet.	*cm.*				
0.35	0	0	0	....	....
1.0	19.8	18.4	33.3	28.3	51.2
2.0	50.3	48.5	72.0	30.1	38.7
3.0	80.8	73.6	98.7	25.1	26.7
4.0	111.3	100.0	100.0	26.4	1.3
5.0	141.8	98.2	97.1	....	....

The slight decrease in the differential deflection at the fifth foot, as compared with that at the third or fourth foot in the experiments with carbon dioxide, is possibly due to the chilling of the radiating disk in the extreme end position, or to absorption of disk radiation by CO_2, a point which will be examined farther on; but the change in the air series at the fifth foot is presumably to be attributed to a different cause. The observations of Table 30 were the first made with apparatus *C*. Intermediate positions were reached by stopping the rod which carries the disk at successive marks, but the end reading was secured by pulling out the disk until its clamp was felt or heard to strike against the end-plate. The supports of the cylinder were not stiff enough to resist the shock, and the entire mass of iron moved to and fro though a sufficient range to produce a deflection of a few divisions on the galvanometer by magnetic influence. Suspecting such an effect, which was, however, irregular, and one for which no correction can be applied, I had the supports stiffened by braces, and the remedy proved effectual. The error only affects the readings on the fifth foot in Table 30, and these have been rejected. Observations made after the insertion of the braces, and with a cold cylinder, to see if any magnetic effect was exerted by the motion of the steel rod, gave a deflection of — 0.29 div. for the outward motion of 4.65 feet. As this is included in possible errors of observation, no correction is applied for magnetic influence.

The relative increments of radiation, given in the last column of Table 40, demonstrate that a layer of carbon dioxide, 3 feet deep, is sufficient to extinguish by its absorption practically all the radiation of the peculiar quality emitted by this gas; and thus that no further increase in the depth of the radiating layer is of avail for adding to the emission of the only rays which this substance is capable of sending forth. If this is a general law, the brilliancy of a glowing gaseous mass (a solar prominence, for instance) depends, after a certain depth has been exceeded, entirely upon the temperature, but not on the dimensions of the layer; and the cooling of a gaseous mass of great depth depends on the radiation of a comparatively shallow layer whose locus travels inward. It might be inferred from the preceding experiments that layers of air and of carbon dioxide, 1 foot deep, and at atmospheric pressure, radiate equally near the temperature of boiling water to an inclosure near the freezing point; but these results require the application of further corrections before the final quantitative values can be stated.

RADIATION FROM MULTIPLE FLAMES.

In order to examine the effect of increasing depth on the radiation of a gas at high temperature, a series of five Bunsen burners, with apertures 2.5 by 0.2 inches, giving flat flames, were arranged so that the flames were presented broadside to the line of sight. Only so much of the flame as could be seen through the narrow aperture of the multiple tin-plate screen was permitted to radiate to the bolometer. The most distant flame was 2 feet from the bolometer; the nearest, 1½ feet. Exposures were made by withdrawing a blackened copper screen containing cold water. The shape of the flame is shown, full size, in fig. 8.



Line of Sight denoted by the arrow.

Flattened Bunsen Flame.

Full size.

Fig. 8

November 15, 1895.

Temperature of room, 14°.8 C. Dew-point 7°.8 C., corresponding to a pressure of aqueous vapor of 7.88 mm., or 8.11 grams per cubic meter, and to an equivalent liquid depth of 0.000 371 cm. in the distance to the nearest flame, and 0.000 494 cm. in the path to the most distant flame.

Battery galvanometer, 100 div.

Shunt = 0.1451. Multiplier = 6.89. Temperature of cold screen, 10° to 18° C.

TABLE 41.

Number of flames.	5	4	3	2	1 (most distant)	1 (nearest)
Depth of flame.	3.0 cm.	2.4 cm.	1.8 cm.	1.2 cm.	0.6 cm.	0.6 cm.
Deflections (Shunted galvanometer)	244.5	217.5	175.5	128.5	69	74
	245	218	176	129	70.5	72
	250.5	219	176	129.5	66.5	73
	252	221.5	174.5	128.5	69	73
	245.5	220.5	177	130	70	73.5
	249	216	177	125	69.5	75.5
	251.5	218	174.5	129.5	66.5	77.5
	250.5	220	173	130.5	71	73
	252.5	214	172.5	126	69	72
	250	220.5	177	130	71.5	72.5
Mean (shunted)	249.1	218.5	175.3	128.7	69.3	73.6
" (unshunted)	1723	1506	1208	887	478	507
Change per 0.6 cm.	217	298	321	395	493	

The deflection on the most distant single flame is 94.2 per cent. of that on the nearest one, a diminution which is probably due to the greater amount of water-vapor traversed by the rays from the flame at the greatest distance, the radiant emission from the flame being largely that of very hot steam, and one especially depleted of its peculiar rays by even a thin layer of its own substance.

The addition of successive flames, each new one radiating through all the previous ones, gives progressively diminishing increments of radiation, as shown in the last line of Table 41. The average depth of each flame was 6 mm., and the indication is that there will be very little increase of radiation for addition of flame-depth beyond 20 cm. For carbon dioxide, the depth of the efficient radiant layer is not over 90 cm. For air, the efficient depth must be many meters.

CONTINUATION OF MEASURES MADE WITH THE RADIATION CYLINDER.

The next four series of measures with the radiation cylinder have been made with a continuously rising temperature. Hence, according to the general theory of the apparatus, the recorded thermometer readings are lower than the true mean temperatures of the air within the cylinder, by amounts which can perhaps be estimated later; but since all of these series have been taken on a common plan, and the rapidity of heating has been nearly the same, the results are comparable.

The curves of heating are given in fig. 9, abscissæ being intervals from the commencement of heating and ordinates being recorded cylinder temperatures.

The rate of heating is a trifle slower for rarified air. Otherwise, the heating curves are similar. The throw of the disk was to its full extent in every case, the radiant depth being 141.8 cm. Deflections were observed in groups of five every six minutes. Only the mean readings are given here.

February 9, 1893.

Cylinder containing air at normal pressure, 737 mm., and nearly dry, but not purified from carbon dioxide.

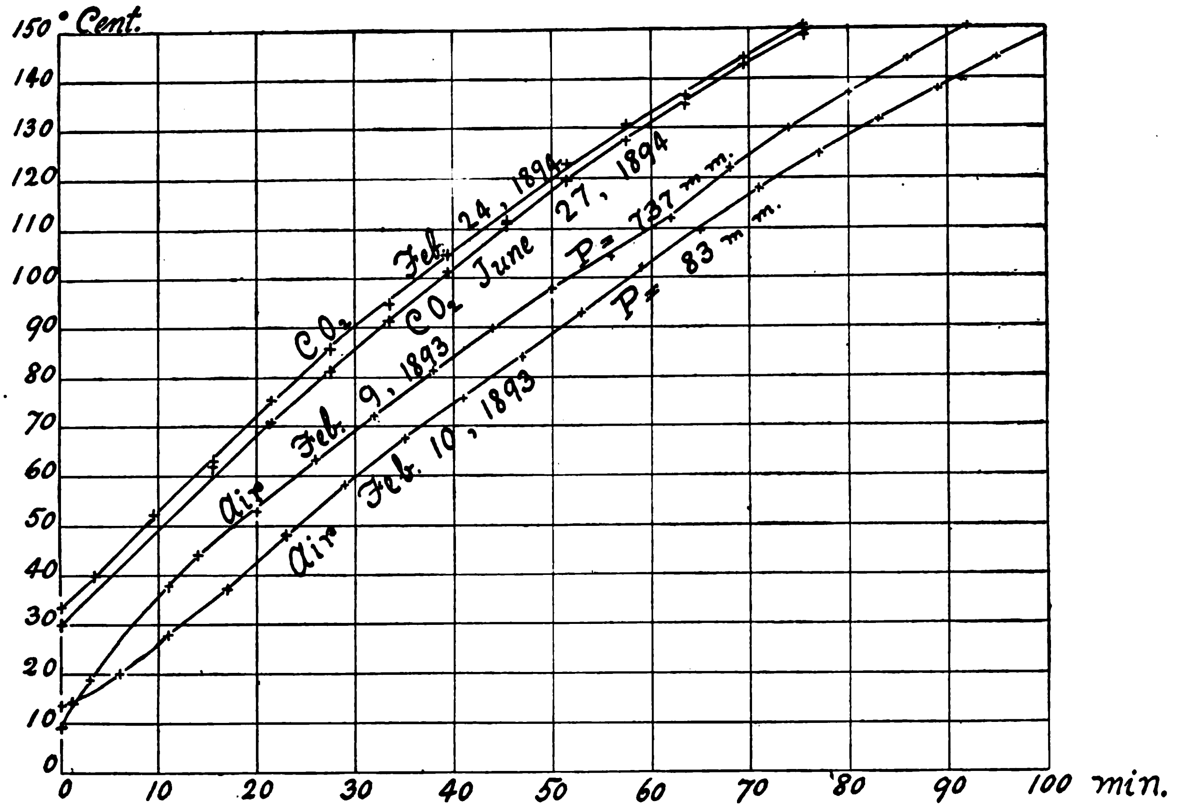


Fig. 9

Temperature of room, at 3h 0m, 11°.1 C.; at 3h 30m, 12°.2; at 4h 0m, 13°.3; at 4h 30m, 14°.4; at 5h 0m, 15°.5.

Mean dew-point, 4°.4 C., corresponding to a pressure of aqueous vapor of 6.24 mm. or 6.50 grams per cubic meter, and to an equivalent liquid depth of 0.000 244 cm. in the absorbent layer.

Lamps lighted at 3h 20m. Burner cocks set at 35 div.

The results are platted in fig. 10 (*a*).

Abscissæ = temperature-excesses (uncorrected).

Ordinates = deflections.

TABLE 42.

Observation No.	Time.	Cylinder temperature.		Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
		Before.	After.					
	h. m.	°	°	°	°	°	*div.*	*mm.*
1	3 8	9.3	....	9.3	16.4	— 7.1	— 0.85	737
2	3 37	43.9	53.2	48.6	17.5	+31.1	+ 8.50	
3	3 43	53.2	63.3	58.3	17.7	40.6	+ 9.21	
4	3 49	63.3	72.1	67.7	17.9	49.8	+11.88	
5	3 55	72.1	81.4	76.8	18.1	58.7	+11.05	
6	4 1	81.4	89.9	85.7	18.3	67.4	+12.78	
7	4 7	89.9	98.0	94.0	18.6	75.4	+12.33	
8	4 13	98.0	104.4	101.2	18.8	82.4	+14.70	
9	4 19	104.4	114.2	109.3	19.0	90.3	+15.87	
10	4 25	114.2	122.1	118.2	19.2	99.0	+16.06	
11	4 31	122.1	130.0	126.1	19.4	106.7	+19.29	
12	4 37	130.0	137.2	133.6	19.7	113.9	+21.66	
13	4 43	137.2	144.0	140.6	19.9	120.7	+22.64	
14	4 49	144.0	150.3	147.2	20.1	127.1	+22.48	

February 10, 1893.

Cylinder containing partially dried air at low pressure.

Temperature of room, 13°.8 to 14°.8 C.

Mean dew-point, 6°.7 C., corresponding to a pressure of aqueous vapor of 7.31 mm., or 7.56 grams per cubic meter, and to an equivalent liquid depth of 0.000 284 cm. in the absorbent layer.

Lamps lighted at $4^h\ 0^m$. Burner-cocks set at 35 div.

TABLE 43.

Observation No.	Time.	Cylinder temperature.		Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
		Before.	After.					
	h. m.	°	°	°	°	°	div.	mm.
1	3 51	13.6	13.7	13.7	18.8	− 5.1	+ 0.26	58.5
2	4 14	28.0	37.1	32.6	19.0	+13.6	+ 3.91	56.7
3	4 20	37.1	48.2	42.7	19.1	23.6	+ 6.73	60.0
4	4 26	48.2	58.2	53.2	19.2	34.0	+ 8.16	64.3
5	4 32	58.2	67.6	62.9	19.2	43.7	+ 8.38	68.5
6	4 38	67.6	75.7	71.7	19.3	52.4	+11.69	72.3
7	4 44	75.7	84.0	79.9	19.3	60.6	+11.09	76.8
8	4 50	84.0	93.0	88.5	19.4	69.1	+12.26	81.8
9	4 56	93.0	102.2	97.6	19.5	78.1	+14.78	86.5
10	5 2	102.2	109.7	106.0	19.5	86.5	+13.99	91.5
11	5 8	109.7	118.1	113.9	19.6	94.3	+15.60	96.5
12	5 14	118.1	125.0	121.6	19.6	102.0	+17.22	101.8
13	5 20	125.0	131.6	128.3	19.7	108.6	+21.43	106.3
14	5 26	131.6	137.9	134.8	19.8	115.0	+22.07	110.8
15	5 32	137.9	144.2	141.1	19.8	121.3	+23.39	116.8

The results are plotted in Fig. 10 (*b*). The cold cylinder leaked at the rate of 5 mm. in 15 min. at the lower pressures. Computing the proportional leakage for three intervals in the above series, and comparing the observed pressures, corrected for the expansion of air by heat, we have:

	mm.
$4^h\ 14^m$ to $4^h\ 44^m$, change of pressure,	56.7 to 76.8
By thermal change, $56.7 \times [1 + (60.6 - 13.6) \times .00367] =$	66.5
Observed leakage,	10.3
Leakage, computed for 30 min. interval,	10.0
Residual,	+0.3
$4^h\ 44^m$ to $5^h\ 8^m$, change of pressure,	76.8 to 96.5
By thermal change, $76.8 \times [1 + (94.3 - 60.6) \times .00367] =$	86.3
Observed leakage,	10.2
Leakage, computed for 24 min. interval,	8.0
Residual,	+2.2
$5^h\ 8^m$ to $5^h\ 32^m$, change of pressure,	96.5 to 116.8
By thermal change, $96.5 \times [1 + (121.3 - 94.3) \times .00367] =$	106.0
Observed leakage,	10.8
Leakage, computed for 24 min. interval,	8.0
Residual,	+2.8

The excess of observed pressure over computed at the higher temperatures is probably to be attributed to the real mean temperature being higher than that assumed from thermometer readings in heating, as explained in the general theory of the apparatus; but it is possible that the leaks may have increased in the course of the process of heating. Leaks in the luting had been started by the previous day's heating and the joints had to be tightened at the beginning of the observations of February 10. Another possible cause of the discrepancy is that some vapor may have been evolved by the heat at the highest temperatures; but in this case some special fluctuation of the readings of the galvanometer might be anticipated, and of this there is no sign.

February 24, 1894.

Cylinder filled with dry carbon dioxide at atmospheric pressure, 748 mm.

Temperature of room, 12°.8 C. at 2ʰ 10ᵐ, to 15°.1 C. at 3ʰ 47ᵐ.

Dew-point, 1°.4 C., corresponding to a pressure of aqueous vapor of 5.05 mm., or 5.32 grams per cubic meter, and 0.000 190 cm. of liquid water in the absorbent air layer.

Lamps lighted at 2ʰ 19ᵐ. Cocks 35 div.

TABLE 44.

Observation No.	Time.	Cylinder temperature. Before.	Cylinder temperature. After.	Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
	h. m.	°	°	°	°	°	div.	mm.
1	2 26	39.8	52.2	46.0	18.2	27.8	+ 3.20	748
2	2 32	52.2	63.0	57.6	18.4	39.2	+ 4.78	
3	2 38	63.0	75.3	69.2	18.5	50.7	+ 4.51	
4	2 44	75.3	85.8	80.6	18.7	61.9	+ 7.63	
5	2 50	85.8	94.8	90.3	18.8	71.5	+ 8.53	
6	2 56	94.8	104.8	99.8	19.0	80.8	+10.73	
7	3 2	104.8	111.5	108.2	19.1	89.1	+ 8.10	
8	3 8	111.5	122.8	117.2	19.3	97.9	+10.80	
9	3 14	122.8	130.8	126.8	19.4	107.4	+12.92	
10	3 20	130.8	136.8	133.8	19.6	114.2	+13.49	
11	3 26	136.8	144.1	140.5	19.7	120.8	+13.45	
12	3 32	144.1	150.6	147.4	19.9	127.5	+15.80	

The results are platted in fig. 10 (*c*).

June 27, 1894.

Cylinder containing dry carbon dioxide at atmospheric pressure, 730 mm. (at 0° C.).

Temperature of room, 29°.4 C., with a rise of one-half degree per hour.

Dew-point, 15°.0 C., corresponding to a pressure of aqueous vapor of 12.67 mm., or 12.71 grams per cubic meter, and to an equivalent liquid depth of 0.000 478 cm. in the absorbent layer of air.

Lamps lighted at 3ʰ 32ᵐ. Burner cocks at 40 div.

TABLE 45.

Observation No.	Time.	Cylinder temperature. Before.	Cylinder temperature. After.	Mean temperature.	Bolometer temperature.	Excess.	Deflection.	Pressure.
	h. m.	°	°	°	°	°	div.	mm.
1	3 51	61.6	70.9	66.3	34.2	32.1	+ 5.59	730
2	3 57	70.9	81.2	76.1	34.2	41.9	+ 6.64	
3	4 3	81.2	91.2	86.2	34.3	51.9	+ 6.34	
4	4 9	91.2	101.2	96.2	34.3	61.9	+ 8.16	
5	4 15	101.2	111.0	106.1	34.4	71.7	+ 9.50	
6	4 21	111.0	119.6	115.3	34.4	80.9	+ 9.38	
7	4 27	119.6	127.6	123.6	34.5	89.1	+10.58	
8	4 33	127.6	134.8	131.2	34.5	96.7	+10.28	
9	4 39	134.8	142.9	138.9	34.6	104.3	+ 9.72	
10	4 45	142.9	148.6	145.8	34.6	111.2	+11.73	
11	4 51	148.6	154.2	151.4	34.7	116.7	+12.69	

The results are platted in fig. 10 (*d*). Fig. 10 (*a*) gives for air a radiation of 24 div. at excess 130° C., or 0.185 div. per degree; and fig. 10 (*b*) gives 24 div. for 125° excess, or 0.192 div. per degree, no appreciable change being produced by rarefaction. Fig. 10 (*c*) gives for carbon dioxide a radiation of 14 div. for an excess of 120° C., or 0.117 div. per degree; and fig. 10 (*d*) gives 14 div.

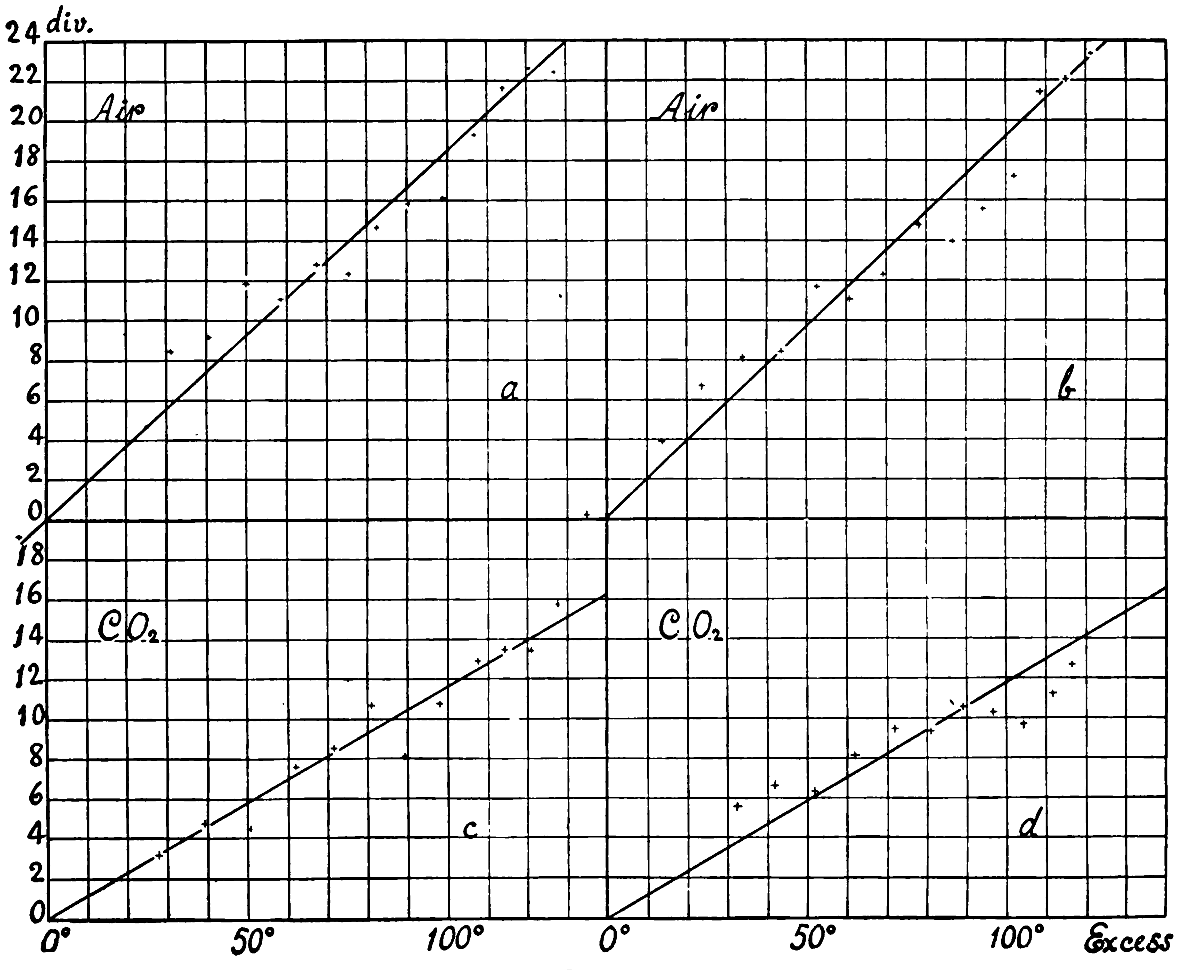


Fig. 10

for 118°, or 0.119 div. per degree, both observations being at atmospheric pressure. Reducing this deflection to the galvanometer constant of 1893, it becomes 0.1254 div., and the ratio of radiations (141.8 cm. layer) is:

$$\text{Air} : \text{CO}_2 \; . \; . \; . \; . \; . \quad \frac{0.1885}{0.1254} = 1.50.$$

This ratio is, of course, only applicable to the limited range of depth and temperature from which it has been obtained. The increase of water in the absorbent layer, in the ratio $\frac{478}{190} = 2.52$, has not affected the radiation of carbon dioxide. The bands of these substances, in the infra-red, overlap to some extent, but if composed of fine lines, they need not interfere.

GASEOUS RADIATION WITH A COOLING CYLINDER (LAMPS EXTINGUISHED).

The next experiments, conducted with a cooling cylinder, should give trustworthy values according to the general theory of the apparatus.

June 28, 1894.

Cylinder filled with dry carbon dioxide.

Temperature of room, 30°.4 C.; of bolometer, 35°.4.

Mean dew-point, 15°.2 C., corresponding to a pressure of aqueous vapor of 12.84 mm., or 12.87 grams per cubic meter, and to a liquid depth of 0.000 484 cm. in the absorbent layer of air.

The measures were to be made near normal pressure, and at points marked with an asterisk, a little carbon dioxide was allowed to flow into the cylinder to restore the pressure. Each deflection in the following table is the mean of five. The first reading in each series corresponds to the maximum temperature and is abnormal:

TABLE 46.

Series 1.

Time.	Cylinder temperature.		Mean temperature.	Excess.	Cooling rate per minute.	Deflection.	Pressure at 0° C.
	Before.	After.					
h. m.	°	°	°	°	°	div.	mm.
2 8							744
2 11.5	133.2	132.8	133.0	97.6	0.13	+15.68	
2 15	132.8	129.9	131.4	96.0	0.73	+12.44	
2 17							731
2 21.3	126.7	124.3	125.5	90.1	1.10	+ 8.71	
*2 23							718
2 29							751
2 32	117.0	112.4	114.7	79.3	0.81	+ 6.32	
2 35							742
2 37	112.4	109.0	110.7	75.3	0.67	+ 4.65	
2 39							737
2 47	105.1	103.8	104.5	69.1	0.48	+ 3.86	
2 48							726

Series 2.

Time.	Before.	After.	Mean temperature.	Excess.	Cooling rate per minute.	Deflection.	Pressure at 0° C.
h. m.	°	°	°	°	°	div.	mm.
3 43							741
3 45.5	136.2	134.4	135.3	99.9	0.36	+14.51	
3 48							734
3 55							728
3 56.5	128.7	125.0	126.9	91.5	1.23	+ 9.52	
3 58							715
3 59.5	125.0	119.9	122.5	87.1	1.70	+ 8.21	
*4 1							706
4 14							741
4 16.5	113.0	109.4	111.2	75.8	0.72	+ 5.66	
4 19							739
4 21	109.4	105.2	107.3	71.9	1.05	+ 4.55	
4 23							733
4 25	105.2	101.7	103.5	68.1	0.88	+ 4.09	
4 27							729

The mean of the observed pressures in the first series is 736 mm.; in the second 730 mm.; and the mean cooling rate is 0°.80 per minute.

On this date a final series was taken with carbon dioxide as the radiant, to see if any effect could be noted from varying the pressure while the temperature remained constant or was cooling very slowly.

TABLE 47.

Temperature.	Excess.	Cooling per minute.	Deflection.	Pressure.
°	°	°	div.	mm.
134.8	99.4	0.53	+10.09	739
135.0	99.6	0.00	+11.43	588
135.4	100.0	0.40	+11.19	401
134.5	99.1	0.20	+12.74	208
133.8	98.4	0.08	+12.35	213

Here a slight increase of the deflection was observed when the pressure diminished.

The next experiments were made with air purified from both aqueous vapor and carbon dioxide. The air entered the apparatus through a series of flasks and tubes. First came two flasks (1 and 2) containing porous chloride of calcium; then (3) a long horizontal tube filled with crushed and chemically pure hydrate of sodium, the stoppers being protected by asbestos. Next (4) came a flask filled with a solution of sodium hydrate in glycerin, through which the air passed in bubbles whose rate of flow could be regulated by the graduated stopcock. After this came (5) another flask of porous chloride of calcium, and last (6 and 7) two flasks containing flocculent phosphoric anhydride. (1) and (2) protect the sodium hydrate from atmospheric moisture; (4) is relied on to absorb the last traces of carbon dioxide. The water coming from the chemical reaction

$$2\ NaOH + CO_2 = Na_2CO_3 + H_2O,$$

is absorbed by (5), (6), and (7).

Finally a bowl of phosphoric anhydride and, in the last experiment, pure sodium were introduced directly into the radiation cylinder to absorb the small amount of impurity coming from leakage.

The leakage being proportionally very much greater at low pressures, after a preliminary exhaustion and filling, the pressure was kept about 50 mm. below the normal for a long time, the outer air flowing slowly through the flasks and completing the purification by successive dilutions.

August 15, 1895.

Pressure, 731 mm. at 0° C.

Temperature of room, 31°.3 C.; of bolometer, 36°.3.

Dew-point, 6°.7 C. Pressure of aqueous vapor, 7.31 mm., or 7.56 grams per cubic meter, equivalent to a liquid depth of 0.000 284 cm. in the absorbent layer. Disk of blackened asbestos.

Temperature in (1) cooling from 100°.0 to 96°.4. Excess 61°.9
" " (2) " " 91 .5 " 89 .3 " 54 .1
" " (3) " " 81 .0 " 79 .0 " 43 .7

Deflections:	(1) div.	(2) div.	(3) div.
	+13.8	+7.2	+6.6
	13.9	8.4	4.2
	14.0	6.1	4.3
	11.7	8.3	4.7
	11.3	8.3	3.1
Mean deflections:	+12.94	+7.66	+4.58

August 17, 1895.

Pressure, 728 mm.

Temperature of room, 29°.9 C.; of bolometer, 34°.9.

Dew-point, 14°.4. Pressure of aqueous vapor, 12.19 mm., or 12.26 grams per cubic meter, equivalent to a liquid depth of 0.000 461 cm. in the absorbent layer. Disk of blackened asbestos.

Temperature in (1) cooling from 92°.0 to 90°.9. Excess 56°.6.
" " (2) " " 79 .5 " 77 .2 " 43 .5
" " (3) " " 69 .4 " 68 .0 " 33 .8
" " (4) " " 60 .0 " 58 .8 " 24 .5

Deflections:	(1) div.	(2) div.	(3) div.	(4) div.
	5.5	3.7	3.0	2.7
	7.2	4.0	3.2	2.9
	6.6	5.8	2.0	3.1
	7.8	3.8	1.3	2.2
	8.0	4.1	1.0	2.5
Mean deflections:	+7.02	+4.28	+2.10	+2.68

August 21, 1895.

Pressure, 735 mm.

Temperature of room, 25° C.; of bolometer, 30°.

Dew-point, 4°.7 C. Pressure of aqueous vapor, 6.37 mm., or 6.63 grams per cubic meter, equivalent to a liquid depth of 0.000 249 cm. in the absorbent layer.

Temperature in (1) cooling from 105°.9 to 105°.0. Excess 75°.5
" " (2) " " 100 .0 " 96 .7 " 68 .4
" " (3) " " 89 .5 " 86 .6 " 58 .1
" " (4) " " 80 .2 " 77 .2 " 48 .7

Deflections:	(1)	(2)	(3)	(4)
	div.	div.	div.	div.
	6.0	7.6	2.6	1.6
	7.4	5.5	3.0	1.1
	9.5	6.4	2.0	2.8
	8.9	5.7	2.1	0.7
	9.3	5.6	4.6	0.8
Mean deflections:	+8.22	+6.16	+2.86	+1.40

August 22, 1895.

Pressure, 738 mm.

Temperature of room, 27° C.; of bolometer, 32°.

Dew-point, 7°.8 C. Pressure of aqueous vapor, 7.88 mm., or 8.11 grams per cubic meter, equivalent to a liquid depth of 0.000 305 cm. in the absorbing layer.

Temperature in (1) constant at 71°.0. Excess 39°.0
" " (2) " " 71 .0 " 39 .0
" " (3) cooling from 71°.0 to 70 .5 " 38 .8
" " (4) " " 70 .5 " 69 .4 " 38 .0
" " (5) " " 69 .4 " 69 .0 " 37 .2

Deflections:	(1)	(2)	(3)	(4)	(5)
	div.	div.	div.	div.	div.
	11.6	6.8	5.3	3.0	2.3
	8.0	5.4	4.8	5.6	3.9
	7.0	6.6	4.2	3.4	2.0
	5.0	6.1	5.6	4.4	3.4
	5.9	4.1	3.3	3.3	2.4
Mean deflections:	+7.50	+5.80	+4.64	+3.94	+2.80

The radiation cylinder on this occasion had been heated for a long time by the two central burners only. The horizontal inequality of temperature produced by the uneven heating persisted until the end of this series. The last reading is nearly normal.

Finally the radiation cylinder was kept at a nearly constant temperature—not far from 100° C.—for a week, the air being in contact with metallic sodium. The following readings were taken during the interval:

September 13, 1895.

Pressure, 733 mm.

Temperature of room, 26° C.; of bolometer, 31°.

Dew-point, 12°.2 C. Water-vapor pressure, 10.57 mm., or 10.71 grams per cubic meter. Equivalent liquid depth in absorbing layer, 0.000 403 cm.

Temperature, 100°.0 C. (steady). Excess, 69°.0.

Deflections: 7.3, 6.3, 8.0, 7.8, 8.2; mean, + 7.52 div.

September 14, 1895.

Pressure, 737 mm.

Temperature of room, 23°.5 C.; of bolometer, 28°.5.

Dew-point, 9°.4 C. Pressure of aqueous vapor, 8.78 mm., or 8.98 grams per cubic meter. Equivalent liquid depth in the absorbent layer, 0.000 338 cm.

Temperature, 97°.8 C. (steady). Excess, 69°.3.

Deflections: 7.0, 8.4, 7.7, 7.0, 4.5; mean, + 6.92 div.

September 19, 1895.

Pressure, 733 mm.

Temperature of room, 28°.8 C.; of bolometer, 33°.8.

Dew-point, 17°.8 C. Pressure of aqueous vapor, 15.14 mm., or 15.04 grams per cubic meter. Equivalent liquid depth in the absorbent layer, 0.000 566 cm.

Temperature, 96°.2 C. (steady). Excess, 62°.4.

Deflections: 8.9, 7.1, 7.2, 9.1, 6.8; mean, +7.82 div.

FINAL CURVES OF APPARENT RADIATION BY METHOD C.

Rejecting the first members of each series, because they are vitiated by inequalities of temperature, the remaining deflections with carbon dioxide on June 28, 1894 (Table 46), form a single consistent series, representing the maximum apparent radiation from this gas, so far as radiation depends upon depth, which deserves exceptional weight (fig. 11). Passing a mean curve

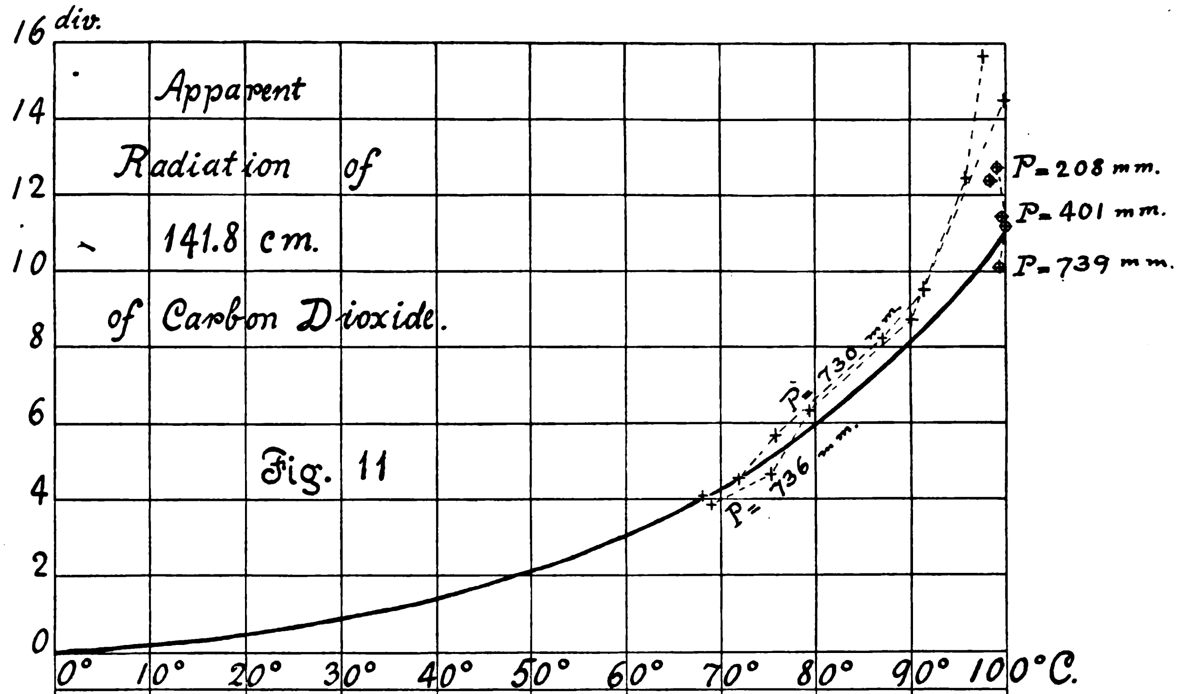

Apparent Radiation of 141.8 cm. of Carbon Dioxide.

Fig. 11

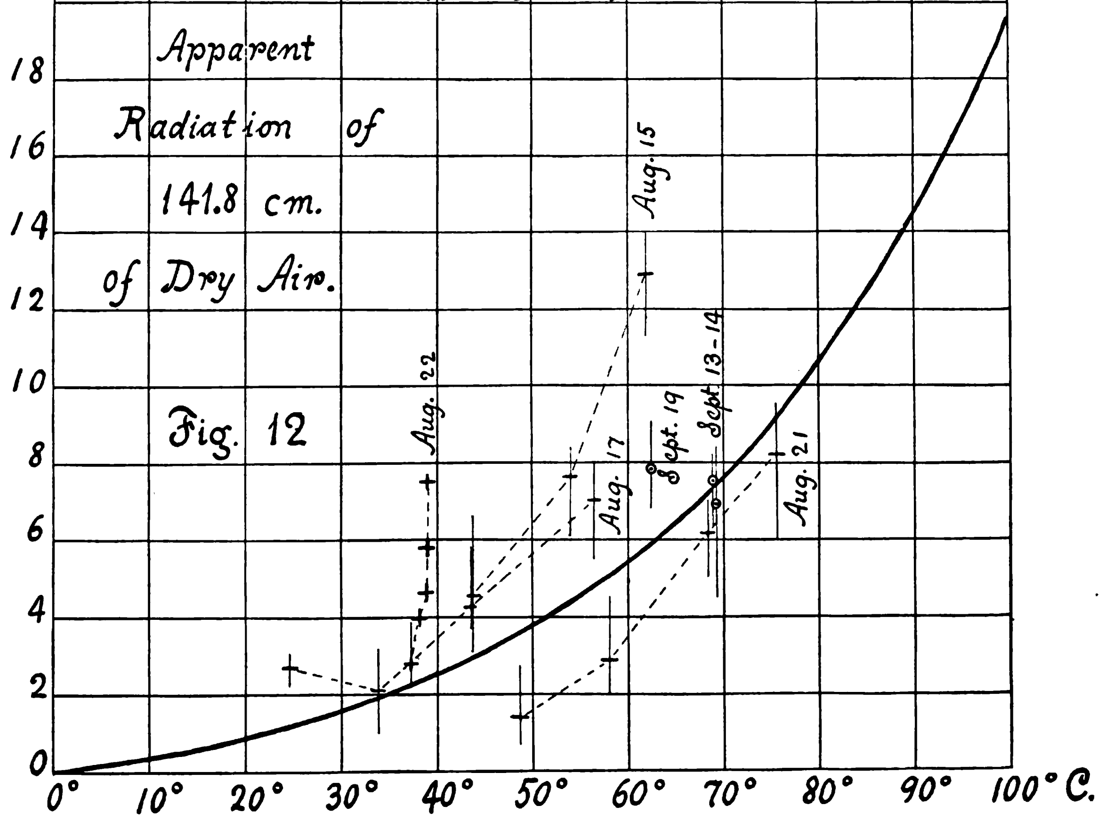

Apparent Radiation of 141.8 cm. of Dry Air.

Fig. 12

through these points and those of Table 47, and multiplying the ordinates by the ratio 1.5, already obtained for air radiation from a layer 141.8 cm. deep, as compared with the radiation of a like layer of carbon dioxide, and reducing to like instrumental conditions, a curve is obtained (fig. 12) which represents, as well as any which I can devise, the considerable range in air values which have been obtained between August 15 and September 19, 1895. The curve falls between the observations of August 17 and August 21, passes between the records of radiation at stationary temperature of September 13 and 14, although considerably below the stationary point of September 19, and is sufficiently below the obviously abnormal curve of August 22 to be free from the suspicion of being affected by any remaining inequality of temperature. The readings of August 21 are a little too small, the rock-salt plate having a deposit of dust on its surface. The observations of August 15 have not progressed far enough to be entirely uninfluenced by inequality of temperature. Even the deflections at stationary temperature may be a little too large on this account, and the curve should pass below them rather than through them. In plotting these variant air values lines have been drawn through the mean positions, showing the extreme range in the deflections (fig. 12).

The observations of carbon dioxide radiation were made in 1894, those of air in 1895. Consequently the ordinates for the curve in fig. 12, obtained by multiplying those of fig. 11 by 1.5, have been further multiplied by the ratio of the galvanometer constants in those years, which, by p. 26, is $\frac{438}{368} = 1.19$, giving with the condition of instruments in 1895 these values for air radiation:

Excess:	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°
Deflection:	0.38	0.86	1.54	2.50	3.78	5.46	7.60	10.59	14.52	19.64

Reduced with the galvanometer constant of 1894, the following table is obtained, giving the adopted apparent radiations of a 141.8 cm. layer for every tenth degree of temperature-excess from 0 to 100°, as read from the smooth curves, the values being expressed finally in absolute units, or radims × $(10)^{-9}$

TABLE 48.

Temperature excess.	10°.	20°.	30°.	40°.	50°.	60°.	70°.	80°.	90°.	100°.
	div.	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*	*div.*
CO_2	0.21	0.48	0.86	1.40	2.12	3.06	4.26	5.93	8.13	11.00
Air	0.32	0.72	1.29	2.10	3.18	4.59	6.39	8.90	12.20	16.50
CO_2*	9	21	38	61	93	134	187	260	356	482
Air	14	32	57	92	139	201	280	390	534	723

* Radiation in ninth-radims.

The measured gaseous radiations are somewhat too small, because the gaseous absorption of disk radiation has been greater with the disk out, thus diminishing the deflection, and because the rock-salt and the absorbent layer of air have kept back a part of the radiation of the hot gas.

By Method B (*ante*, p. 44), the radiation of 1 meter of *moist* air is about 0.000 000 104 radim at 40° excess.

By Method C, the radiation of *dry* air, reduced to the same depth, is 0.000 000 065 radim at 40° excess.

Both radiations have been diminished by absorption. In particular, the result by Method C requires an increase of about one-third on account of the absorption by the rock-salt plate. The hot moist air might be expected to radiate more powerfully than dry air at the same temperature, and the remaining difference is probably attributable to this qualitative distinction.

Although the affinity of rock-salt for moisture made the result of the experiment somewhat problematical, I decided to try to measure the radiation of water-vapor by Method C, allowing steam to run into the hot and partially exhausted cylinder. I had supposed at the time of making this experiment that the gradual introduction of steam into a *hot* partially exhausted vessel would not be attended by liquid condensation. The result proved that the flow of steam was too rapid, and that the cylinder should have been full of air at the start, the air-pumps being used merely to keep the pressure from rising much above normal. Hirn, in 1862, had found that the sudden diminution of pressure in steam at 152° C. and 5 atmospheres pressure, gave a cloudy condensation, but this result was unknown to me until I read it in Preston's *Theory of Heat*, published about the time of my observations. I regret that the simple expedient of allowing air to remain in the cylinder while the steam was entering did not occur to me until after the apparatus was dismounted.

EXPERIMENT ON THE RADIATION OF STEAM.

Temperature of room, 33° C.; of bolometer, 38°.

Dew-point, 3°.1 C.; pressure of aqueous vapor 5.70 mm., or 5.96 grams per cubic meter. Equivalent liquid in the absorbent layer = 0. 000 224 cm. After exhaustion to 79 mm. the mean temperature of the radiation cylinder was 132°, cooling at the rate of 1°.5 per minute, and the mean deflection from air, at 99° excess, was + 13.02 div. The heater, containing boiling water, was then connected until the pressure reached 731 mm., the temperature meantime rising to 142°, or to an excess of 104°. A mean deflection of + 5.20 div. was then obtained, followed by another of + 4.84 div., excess 101°. Within 15 minutes after these readings, the pumps having been worked, the pressure had diminished to 126 mm., temperature 135°, excess 97°. The mean deflection had increased to + 25.62 div., the temperature being nearly stationary.

Undoubtedly, the watery condensation at first precipitated a film of moisture, or dew, on the rock-salt, which diminished the deflection by its irregular scattering of the rays; but when the pressure was removed, this film evaporated, and even through the now corroded rock-salt plate, which transmitted scarcely more than two-thirds of the radiation, this deflection of 25.6 div. was measured. I infer that with a clear plate, something like 38 div., or about 70 per cent. of the radiation of lampblack at a like excess, might be obtained from a layer of steam, at 126 mm. pressure, 142 cm. deep. Under these circumstances, and within the range of my observations, water-vapor (with no allowance for absorption by the vapor in the air of the room), radiates about three times as powerfully as air. In small amount, however, water-vapor radiates much more than the simple proportion of the quantities would indicate.

EXPLANATION OF RESULTS AT LOW PRESSURES.

I have alluded (*ante*, p. 54) to the small difference between deflections at ordinary and at low pressures as being at first sight surprising; but the explanation is simple enough. According to Dulong and Petit (*Ann. de Chimie et de phys.* (2), tome 7, p. 337, 1817), convection in air at 720 mm. pressure removes from a hot body 2.548 times as much heat as at 90 mm. pressure; but since the mass of unit volume is eight times as great at the higher pressure, the air heated by convection at the lower pressure, (1) if equal volumes are set in motion, must get $\frac{8}{2.548} = 3.139$ times as hot; or else, (2) if the air gets no hotter, 3.139 times as large a volume of low-pressure air must move in the convection current in the same interval of time.

Under identical thermal conditions, the radiation cylinder being heated by four large Bunsen burners, with stop-cocks set at 35 div., air, first at 737 mm. and second at 83 mm. pressure, was heated to the same extent (80° C.) in one hour, with little difference in the radiation from the heated air column. The final temperature of the entire body of mixed air may be nearly the same in either case, but the radiation through the limited aperture should be greater in the first condition, because radiation increases more rapidly than temperature, and the smaller volume of superheated low-pressure air should have the greater radiant efficiency. The true rate of increase of gaseous radiation with rise of temperature, as will be eventually shown, is such that if the temperature is three times as great, the radiation is increased in something like the ratio of eight to one. Hence if the volume of rarefied air has one-eighth the mass, and is three times as hot as the same volume of high-pressure air, the radiation per unit of mass (condition 1) will be eight times as great for the air of smaller density, or identical per unit of volume for either high or low pressure. The actual rate of heating depends on that of the iron cylinder, and not on the thermal capacity of the air, whose mass is relatively insignificant. The result of the measurements of gaseous radiation implies that the volume of air set in motion in the unit of time by convection is independent of the pressure, but that the temperature of this volume is such that the radiant effect of unit mass increases in inverse proportion to the mass of unit volume. The argument also implies that, at the same temperature, the radiant effect is proportional to the mass of the radiating gas, and is independent of the volume which this mass may occupy, always with the provision that the mass is a small one, or not great enough for the self-absorbent action of the gas on its own radiations to produce any essential modification of the radiant power.

Since the heating of the bottom of the iron cylinder by the flames was far from uniform, it is evident, as has been demonstrated already in other ways, that the measured radiation does not proceed uniformly from the entire mass of air in range with the bolometer, but from local columns of hot air rising over the hotter spots in the iron and passing into the field of the bolometer-aperture at a volumetric rate, as appears from the present argument, which is the same in the rarefied as in the denser air. It has been shown that the disposition, or thermal condition, of the components of the radiating mass at the same mean temperature, and thence the combined radiation of the whole, is different according as the cylinder is heating or cooling, and that the true air radiation probably lies near the values obtained with negative thermal rates. It is also found that the emission of gaseous radiation increases at a more rapid rate than the temperature, so that if ordinates represent radiation and abscissæ temperatures, the curve should be concave upward. Nevertheless, with rapid heating the observations are well represented by a straight line, evidently because the diminishing rate of heating at the higher temperatures gives less powerful convection. Small but excessively heated volumes, giving the larger part of the radiation, then become less predominant, as equilibrium approaches, and the diminution of the convection-correction cuts off the more rapid rise of the energy-curve which would otherwise occur at higher temperature.

It is possible that the apparent radiation of carbon dioxide, at constant temperature, increases at low pressures (as indicated in Table 47, p. 67) by not more than 30 per cent. of the value at normal pressures; but the variation is not beyond the limits of error of the observations on which it rests.

According to Dulong and Petit (*loc. cit.*), the cooling power of air, as far as it depends on pressure, is represented by the ratio $p^{0.45} \div p_1^{0.45}$, and that of carbon dioxide by the ratio $p^{0.517} \div p_1^{0.517}$. Hence the influence of change of pressure upon convection is greater for carbon dioxide than for air, but this is open to various interpretations. A part of the removal of heat by gaseous contact is due to mass convection, and part to the penetrative power of the flying molecules, as G. Johnstone Stoney has demonstrated (On the Penetration of Heat across Layers of Gas, *Phil. Mag.* (5), vol. 4, p. 424, Dec., 1877); but in either mode the effect finally depends partly on the capacity of the gas for heat, and this, for equal volumes, is greater for carbon dioxide than for air in the ratio $\frac{3307}{2375} = 1.393$; while in part the magnitude of the effect is connected with molecular velocity, which is greater for air in the ratio $\frac{487}{397} = 1.227$. The combined effect can only be found by experiment. At normal pressure the cooling by carbon dioxide is 0.965 of that by contact with air, but at low pressures the relation is reversed.

METHOD D.—RELATIVE RADIATION OF AIR AND STEAM, AND OF CLEAR AND SMOKY AIR.

In this method the cylinder was provided with a pressure gage, recording in pounds per square inch to a pressure of 15 pounds above the normal. The cylinder then served as a reservoir for either compressed air or steam. On opening a stopcock the air, or steam, issued from a hot brass tube, one-half inch in diameter, as a hot jet between the bolometer and a blackened screen containing water at the temperature of the room. The bolometer was protected from air currents by a rock-salt plate. In the first experiments partially dried air was used. Three dishes containing flocculent phosphoric anhydride, were placed on the floor of the compression cylinder, and air, compressed by a pump, was forced into the heated cylinder, but was not allowed to stand long enough to become thoroughly dried.

The objections to the method are that the amount of the radiating gas can not be accurately measured, and that its temperature, after leaving the nozzle, is lowered by mixture with cold surrounding air. For these reasons the deflections have only a relative value. The temperature of the room, owing to the escape of considerable volumes of hot air or steam, rose rather rapidly, but was kept within bounds by opening windows.

September 28, 1895.

Temperature of room varying from 16°.7 C. to 22°.0.

Mean dew-point, 8°.3 C. Pressure of water vapor, 8.15 mm., or 8.37 grams per cubic meter.

Temperature of air blast on issuing, (1) 146°, (2) 221°.

Mean deflections, (1) 1.94 div., (2) 3.45 div.

September 30, 1895.

Mean temperature of room, 15°.6 C.

Mean dew-point, 6°.1 C. Pressure of aqueous vapor, 7.02 mm., or 7.27 grams per cubic meter.

After several charges of steam had been allowed to escape in order to remove the air from the cylinder, readings were begun. The deflections increased as the steam became purer. The following successive readings were taken: + 4.6, + 5.8, + 7.9, + 8.1, + 9.8, + 9.8, + 10.3, + 11.0, +9.5, + 11.0, + 11.6, + 11.0. The temperature having fallen slightly during the last readings, the cylinder was left to heat a little longer, and the final measures were made.

Temperature of steam blast on issuing, 202° C.

Mean deflection, + 12.39 div.

Corresponding air deflection, + 3.07 div.

Steam radiation four times as great as that of air. The undried air between the bolometer and the jet has probably absorbed more of the aqueous radiation than of that from the air, so that the ratio is, if anything, too small.

The superheated steam, on issuing, formed mist, and a part of the radiation comes from finely divided liquid; but the next experiment does not indicate that these condensed particles can have any great effect on the result.

In order to test the possibility of appreciable radiation from fine particles suspended in air, two wide-mouthed bottles were prepared with dipping inlet and free outlet tubes, the first one-fourth filled with strong ammonia water, the second containing about as much hydrochloric acid. Air from a foot bellows was blown through the coupled flasks, and a dense column of chloride of ammonium smoke arose immediately in front of the hot blast nozzle. As soon as the hot-air blast was turned on, this cloudy column was sheared off and mingled with the hot air. About one-fourth as much air issued from the smoke jet as from the hot blast, but the latter can not have been cooled thereby much more than in the ordinary suction and mingling of the surrounding air. The particles being excessively fine, and comparable in their dimensions with the shorter waves of light, as shown by the blueness of the smoke where it was thinner, the microscopic crystals must have taken the temperature of the air in which they were immersed almost instantly. The cloud appeared fully as dense as the mist from the condensed steam in the previous experiment.

October 3, 1895.

Temperature of room, 17°.7 C. to 18°.8.

Mean dew-point, 4°.4 C. Pressure of aqueous vapor, 6.24 mm., or 6.50 grams per cubic meter.

Temperature of hot-air blast, 200° C.

The range of pressure was a little lower than in the experiments of September 28, and the deflections are therefore a little smaller, but all are comparable with each other.

TABLE 49.

First series.	Second series.	Third series.
Air clear.	Air cloudy with NH_4Cl.	Air clear.
div.	*div.*	*div.*
+1.6	+2.0	+2.4
2.7	1.8	2.0
1.7	2.6	1.2
2.3	1.3	0.7
2.4	1.3	4.0
0.7	2.8	2.1
3.9	2.0	2.8
2.0	1.1	1.2
1.5	2.5	1.4
1.5	1.5	1.2
1.2	2.1	2.3
Means +1.95	+1.91	+1.75

There is no appreciable difference between the radiation of clear and of smoky air in small masses, but it would not be safe to generalize, from this experiment, in regard to radiation from large masses of smoky air.

COMPARISON OF SOME OF THE PRECEDING RESULTS WITH THOSE OF TYNDALL.

The experiment suggested by Professor Abbe in its simplest form (Prefatory note, pp. 1–2) has been partly realized in Method D, with the exception of the unessential addition of a background at the temperature of melting ice, and it has also been performed by Tyndall (*Contributions to Molecular Physics in the Domain of Radiant Heat*, p. 42 *et seq.*, American edition of 1873.) As a method of heating an air jet, Professor Tyndall's placing of a hot copper ball within a ring nozzle may have been efficient, but neither the temperature nor the mass of the air can be accurately measured in this way. The results are therefore only qualitative. The deflection from hot air being 0°, that from carbon dioxide is given as 18° (p. 43 *loc. cit.*); but this does not fully express the facts. It is true that when air was turned on through the nozzle the deflection did not increase, but hot air was already passing before the thermopile by simple convection. We read further:

> The radiation from air, it will be remembered, was neutralized by the large Leslie's cube, and hence 0° attached to it merely denotes that the propulsion of air from the gas holder through the Argand burner (or annular nozzle) did not augment the effect.

The 18° from carbon dioxide is therefore a differential effect, and requires the original deflection, without compensating cube, for its interpretation, but this is nowhere stated.

The jet of heated gas in Tyndall's experiment was of relatively small thickness. With a deeper layer the relative position of the two gases in question, as radiants, may be more nearly equal, since, as I have shown, air radiation from layers increasing up to several feet in thickness, varies nearly as the depth, while the radiation of carbon dioxide soon reaches a maximum.

Variations in the ratio of radiation with increasing depth are noteworthy in other gases, as in Tyndall's *Contributions* (p. 97), where a layer of olefiant gas (C_2H_4) having a depth of eleven units, radiated 1.62; and one of air of the same depth, containing one-sixtieth of ether-vapor $(C_2H_5)_2O$, radiated 5.82, the radiation from unit-depth of each gas being taken as unity.

The figures quoted above for radiation of air and carbon dioxide are of an indeterminate ratio, but the absorption of 33 inches of carbon dioxide for radiation from a copper plate, "raised to a temperature of about 270° C." (*loc. cit.*, p. 72), is stated (*loc. cit.*, p. 80) to be ninety times that of air. Even if the radiations of large masses of air and carbon dioxide are equal at some specified temperature, those of thin layers or jets must nevertheless be very unlike, the radiation from the thin jet of air being much smaller than that from a carbon dioxide jet. Other temperatures may yield different radiation-ratios for the two gases, while absorption varies at a still different rate. Consequently, no safe inference as to radiation-ratios can be drawn from those for absorption.

This is shown by the following observations by Paschen for the principal band in the spectrum of carbon dioxide at 4.25μ (*Wied. Ann.*, Bd. 51, S. 26, 1894):

TABLE 50.

Temperature of 7 cm. layer of CO_2.	Intensity of radiant emission.	Absorption by hot + cold CO_2.
° *C.*	*mm. div.*	*Per cent.*
17	0	89
183	17.5	77.5
290	60	68.6
377	118.7	36.7
480	261	19

The absorption is that produced within the limits of the band on the spectral energy-curve of blackened platinum at 400° to 500° C. The small remaining absorption band at the highest temperature has a wave-length 0.17μ shorter than the corresponding emission band, and is due to cold carbon dioxide in the air of the room, the radiation of the hot gas very nearly neutralizing the absorption by the hot gas at 480°.

On page 95 of the *Contributions*, Tyndall gives the ratio of apparent radiations from carbon dioxide and air, dynamically heated by compression, as 3:1, and on page 186 deflections are given whose ratio is 2:1. But these figures are not considered entirely trustworthy, since the radiation measured is supposed to be, to an uncertain extent, that of the end plate and walls of the containing tube, heated by contact with the hot compressed gases; and any differences in the observed radiation are to be attributed partly to the varying readiness with which heat is transferred by conduction and convection from the gas to the solid, and partly to differences in the amounts of heat produced by compression and transferred in this manner. Professor Tyndall, in pointing out some of the defects of the arrangement, says:

> A brass tube 3 feet long and very slightly tarnished within was used for dynamic radiation. Dry air on entering the tube produced a deflection of 12°. The tube was then polished within and the experiment repeated; the action of dry air was instantly reduced to 7°.5. The rock-salt plate at the end of the tube was then removed and a lining of black paper 2 feet long was introduced. The tube was again closed, and the experiment of allowing dry air to enter it repeated. The deflections observed in three successive experiments were 80°, 81°, 80° [corresponding to a force nearly 70 times as great as the first]. * * * A coating of lampblack within the tube produced the same effect as the [black] paper lining; common writing paper was almost equally effective. (*Loc. cit.*, p. 187.)

Now, the paper, being a poor conductor, must acquire on its inner and radiative surface, by direct contact with the dynamically heated gas, a higher temperature than the brass, in which any gain of surface temperature is quickly distributed to deeper layers of metal; but the thin coating of lampblack, backed by conducting metal, is in an intermediate position as a conductor, and might be expected to take on its radiating surface a temperature at any rate lower than that of the paper; yet both blackened paper and blackened brass are said to have behaved alike. Tyndall's explanation that the deflection of 7°.5 is mainly due to radiation from brass to which heat from the compressed air has been transferred, can hardly be maintained without modification, since blackened brass is not 70 times as good a radiator as bright brass, and no inconsiderable part of the 7°.5 may have been true air radiation. I shall return to this point subsequently (p. 110) with fresh material for a more searching test of its truth.

The long tube in Tyndall's research was made of polished metal, and the thermopile was provided with its conical polished reflector, in order to secure the advantage of larger galvanometer deflections, through multiple reflections at large angles of incidence on the inner walls of the tube in those experiments where an independent source of radiation was situated at or beyond the farther end of the tube. When such a tube is used for the dynamic heating of a gas, a large part of the heat produced by gaseous compression is unquestionably transferred to the walls of the tube; but since the mass of the gas and its thermal equivalent are small, while those of the tube are at least several hundred times greater, the tube can not become much heated unless the process is repeated a great many times. The large deflections from lampblack and paper are possibly produced by a special condensation and development of heat in the pores of these substances. The argument on page 186 of the *Contributions*, which makes a "residual deflection of 6°" (after absorption by an extra 13 inches of quiescent carbon dioxide) represent the radiation of polished brass, does not appear to be conclusive, and, in fact, is put forth rather as a surmise.

Admitting the deflections to be of genuine gaseous origin, Tyndall's observations would make a 3-foot layer of carbon dioxide radiate two or three times as much as air. In my experiments the air apparently radiated twice as strongly as the carbon dioxide. In view of the very powerful radiation from water-vapor, and of the difficulty with which this substance is completely eliminated, it may be urged that my samples of air were not dry; but since greater precautions were taken in drying the air than in drying the carbon dioxide, the latter being merely passed through several flasks of porous calcium chloride, while the air, in some of my experiments, had stood for a week in contact with phosphoric anhydride, I do not think that the larger radiation, where air was used, can have proceeded from aqueous vapor in my samples. Only one of my air series gave deflections as small as for carbon dioxide, and this I have had to discredit, owing to a deterioration of the rock-salt plate.

Thus far we meet only uncertainty and discrepancy, but if the reader will have patience all of this shall eventually be cleared away.

It is desirable to have a more careful analysis of Tyndall's experiment than is given in the original memoir. Where the most distant part of the tube was set off as a radiant chamber by a rock-salt partition the direct radiation of its contained gas or walls was received under a smaller angular aperturé and with proportionally smaller effect than where the partition was nearer to the thermopile; but the concentration of the beam reflected from the polished cylindrical walls of the tube was nearly the same in either case. The diameter of the tube is not stated. I will assume it to have been 2.4 inches, as in another case, and the distance of the thermopile from the nearer end of the tube to have been 6 inches, and thus compute the angular areas of the sections on these assumptions. The lengths and deflections in the following table are taken from Tyndall's Table XXXV for carbon dioxide, and the radiant energies are deduced from the deflections by the calibration of the galvanometer. (*Contributions*, p. 57.)

d_1 is the distance in inches to the nearest section.
d_2= " " " " " " farthest "
$l = d_2 - d_1$ = the length of the radiating column.
a_1 = the angular area of the nearest section.
a_2= " " " " " farthest "

TABLE 51.

	1	2	3	4	5	6
d_1	52.6	40.0	19.1	6.0	6.0	6.0
d_2	55.4	55.4	55.4	19.1	40.0	52.6
l	2.8	15.4	36.3	13.1	34.0	46.6
a_1	7	12	32	511	511	511
a_2	6	6	6	52	12	7
$(a_1+a_2)\div 2$	6.5	9	29	281.5	261.5	259
Deflection	1	3.7	16.8	17.5	23.3	33.6
Radiation	1	3.7	17.2	18.0	25.7	48.6

Between (4) and (5) there is an increase of 20.9 inches in the length of the radiating column, and the radiation is greater by 7.7 units; but with a further addition of 12.6 inches to the length in (6), the radiation gains 22.9 units, or three times as much as for the larger increment of length in (5). Table XXXIV, for carbon monoxide, gives a very different relation for the same distances, the increment of radiation in (5) being 10.4 units, and in (6) 6.0 units, numbers which are nearly proportional to the gain in length. I have no hesitation in saying that the deflection from CO_2 in (6) is a mistake. The 33°.6 is possibly a misprint for 23°.6, since, as I have shown, there is no increase in the radiation of carbon dioxide beyond the third foot.

The deflection in (1)—Table 51—is too small for use; but with a trifling addition to the radiations in (4) and (5), reducing them to the lengths of (2) and (3), we may make the following comparison:

TABLE 52.

Length of radiating column.	Radiation CO_2.	Ratio.	Mean angular area.	Ratio.
Inches.				
36	17–26	1:1.53	29–261	1:9
15	4–19	1:4.75	9–282	1:31
Ratio of ratios,		1:3.10		1:3.44

The changes seem to be mainly due to differences in the angular area, but this influences principally the radiation which comes directly to the thermopile, and the total radiation from the gas is made up approximately as follows:

Length.		Reflected radiation.	Direct radiation.	Total.
15 inches	(2)	3.5	+ 0.5	= 4.0
	(4)	3.5	+ (0.5 × 31)	= 19.0
36 inches	(3)	15.9	+ 1.1	= 17.0
	(5)	15.9	+ (1.1 × 9)	= 25.8

These radiations appear to be genuine, but there is no conclusive evidence that the radiation of polished brass has contributed to them appreciably. The observations on air are not given in detail, and we only know from page 186 that whereas the 3-foot layer of CO_2 gave a deflection of 16°.8, dry air gave 8° or 9°.

The temperatures of the gases are not so easily found. In general, the temperature of a gas being the sum of the kinetic energies of its molecules, divided by their number, may be very differently constituted according as the limits of variation of molecular velocity are wide or narrow. Radiation and absorption within the gas need also to be considered. In the present case the radiation has been measured in the midst of a complex series of operations, and we do not know even approximately what proportion of the heat of compression has been ceded to the metal. Professor Tyndall has attempted a thermometric measurement of the temperature of the dynamically heated gas, which may be given for whatever it is worth. He "had the tube perforated and delicate thermometers screwed into it air-tight. On filling the tube the thermometric columns rose, on exhausting it they sank, the range between the maximum and minimum amounting in the case of air to 5° F." (*loc. cit.*, p. 45). If the proportion of heat transferred to the walls is the same in the two gases, we must conclude that at excesses of a few degrees carbon dioxide radiates more than air; but the observation is open to the interpretation that the proportion of heat given to the walls is not the same for either gas, and the precise ratio has still to be determined. Some variations in the ratio of gaseous radiations at different temperatures need not surprise us, since the radiations are made up of bands of very different wave-lengths with various rates of increase by change of temperature. Even solid bodies may have spectral energy-curves of quite different shape, as I have shown in a comparison of the spectra of the Welsbach light and of the illuminating gas flame of an Argand burner. ("Further considerations in regard to laws of radiation," *Astrophysical Journal*, vol. 4, p. 45, June 1896). The relative radiations of particular wave-lengths for these lights vary nearly as 1 to 4 in different parts of the spectrum, the spectral energy-curves crossing and recrossing, and much wider ranges occur in gases where each band has a law of its own. Before arriving at a more definite conclusion a further study of the relation between gaseous radiation and absorption must be made.

MODIFICATION OF ATMOSPHERIC RADIATION BY THE ABSORPTION OF CONSTITUENT GASES AND VAPORS.

Having made a preliminary clearing of some of the sources of error incidental to the apparatus, the method of observation, and the properties of matter, we are now prepared to take up a very important subject—the modification of radiation from gases or solids by gaseous absorption.

Gaseous radiation and absorption are so intricately interwoven that one can not be explained without also considering the other. Observations of gaseous absorption exist in great abundance, but those on gaseous radiation are comparatively few. It is largely in consequence of this one-sided distribution of evidence that so many questions in this department remain open, and that others which have really been settled for a long time do not obtain recognition or are reopened on insufficient grounds.

The chief absorbent of the Earth's atmosphere is water-vapor, but its action is complicated by the relation between vapor and mist. Even considerable changes in atmospheric aqueous vapor in warm weather, if unattended by misty condensation, produce only slight variation in the direct rays of the midday sun, not, however, because water-vapor does not exercise a great absorption, even on solar rays, but because so much moisture is always present in warm weather that nearly all of the rays absorbable by aqueous vapor have been eliminated, and the remaining radiation is comparatively transmissible. Haze, however, of whatever description, whether formed of mineral particles, smoke, or finely divided liquid or solid water, acts at all seasons, and independently of the amount of the vapor of water dissolved in the air. Mist and haze have little effect on the emission of radiations of long wave length from air by virtue of its own temperature, or on the transmission of long ether-waves by the atmosphere, but they have great influence in stopping and scattering those short ether-waves which are especially prominent in sunlight.

Ferrel says (*Recent Advances in Meteorology*, p. 56, ¶ 43, 1886) "the difference in the intensity of the solar rays at the earth's surface at sea level, when the atmosphere is very clear and when it is somewhat hazy, is small, and therefore the whole diminution of intensity in passing through is due mostly to the pure atmosphere;" but this is not correct. The *direct* rays of the sun are much impeded by haze, but are nevertheless nearly as effectual in warming the earth's surface indirectly, because a large part of the rays scattered by the haze still reaches the earth as sky radiation, which bears an increasingly large proportion to the direct solar rays as haze grows denser. In a general way, this influence of the scattering of light by fine particles is recognized by Ferrel on page 59 of the same work, but its application to the point noted on page 56 escaped his attention.

Other inconsistencies occur in the same connection. Thus, on page 59, we read: "It is thought that *pure dry air absorbs very little* of the sun's [radiant] heat in its passage through to the earth. If so, *the loss of intensity must be caused mostly*, in this case at least, *by the irregular reflections* in all directions." But at the end of the same paragraph it is said that *these reflections* "*depend very much in some way upon the vapor* contained in [the clear atmosphere] where it exists. But as this is found mostly in the lower strata near the earth's surface, and only in a small measure in the middle and upper strata of the atmosphere, *its effect is small in comparison with that of the whole depth of a dry atmosphere.*" The only idea which I can derive from the passages which I have italicized is that pure, dry air influences the sun's radiation very little, and mainly by irregular reflection, while water-vapor is even less effective. The last inference is further emphasized in paragraph 44, page 56: "According to the experiments of Dr. Tyndall on the diathermancy of a small portion of air contained in a tube, with regard to heat radiations from terrestrial sources the diathermancy of clear air depends almost entirely upon the aqueous, invisible vapor in it, seventy times as much heat, according to the result of the experiments, being absorbed by it as by the dry air through which the rays pass. This result, however, differs very much from that which had been obtained by Magnus in experiments on the same subject, and this gave rise to considerable discussion between these physicists, Magnus maintaining that the absorption of heat in Tyndall's experiments was by a film of condensed vapor on the inside of the tube through which the rays passed. And this seems really to have been the case, according to experiments which have since been made to verify the results." Nevertheless the opinion is repeatedly expressed elsewhere (as on page 57 *loc. cit.*) "that aqueous vapor in some way diminishes the diathermancy of the atmosphere to terrestrial heat radiation." The only inference which I can draw is that the entire subject was in a state of hopeless confusion in the mind of one who has elsewhere exhibited extraordinary keenness of intellectual perception. The authority of so great a master as Ferrel perhaps has something to do with the fact that the subject still remains obscure. Most of the errors have been repeatedly refuted, but the refutations fail to attract attention.

The fallacy of Magnus, who asserted that he got an absorption of 14.75 per cent. from dry air,[*] where Tyndall found practically none, has been abundantly exposed. Tyndall showed that the glass plates which Magnus used to close his glass vacuum tube must have been heated by absorption of the radiation which passed through them, acting thus as secondary sources of radiation, and that, being chilled by convection, their thermal effect was diminished on admission of dry air. Tyndall used end plates of the feeble absorbent, rock-salt, whose thermal change was relatively small, and this prevented the error in question in his measures. With the glass plates used by Magnus the absorption of so potent a substance as aqueous vapor, being greatly masked or reduced by the nontransmission of radiation by glass in that region where aqueous absorption is chiefly exercised, was further completely overwhelmed by convection, and remained undetected from these causes, combined with lack of sensitiveness in the measuring apparatus.

On the other hand, Tyndall does not completely meet the criticism that a portion of the absorption attributed by him to aqueous vapor may have been due to a very thin film of liquid water condensed on the metallic reflecting surface of his tube, but contents himself with showing that substantially the same relative absorptions were obtained when blackened tubes were used, and finally with tubes so wide that the radiant beam concentrated by a rock-salt lens did not touch the walls, so that condensation could not have had any material influence on the result. (*Contributions*, etc., p. 394.) Magnus, in instituting his criticism, overdid the matter, claiming that all of the absorption, measured by Tyndall and attributed by him to aqueous vapor, was due to the liquid film. Lecher and Pernter (*Sitzb. der k. Akad. der Wissensch. zu Wien*, July, 1880; *Phil. Mag.*, (5) Vol. 11, p. 1, Jan., 1881) in repeating the charge have overlooked the experiment with the rock-salt lens. The claims so far made rest upon mere assertion, but the following considerations, based on internal evidence drawn from the experiments as published, indicate that further elucidation is desirable.

It is to be remembered that in his earlier measures, owing to the insensitiveness of his heat-measuring apparatus, Tyndall used a wide-angled conical reflector to concentrate the rays upon his thermopile, and transmitted the radiant beam through polished tubes in order that radiation, proceeding from the source under a wide angle, might be fully utilized by multiple reflections. Of course the mean path of the rays was somewhat longer than the tube.

Professor Tyndall makes the following statement:

> The absorption is exerted when only a small fraction of an atmosphere is introduced into the tube, and it is proportional to the quantity of air present. This is shown by the following table, which gives the absorption, by humid air, at tensions varying from 5 to 30 inches of mercury:

HUMID AIR.

Tension.	Absorption.	
	Observed.	Calculated.
Inches.		
5	16	16
10	32	32
15	49	48
20	64	64
25	82	80
30	98	96

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[*] The numerical value depends entirely upon the disposition of the apparatus, and has no connection with the absorption of air. Thus, Dr. Franz, by using a 3-foot tube lined with black paper, which cut off internal reflection and diminished the heating of the glass end plates, had obtained an apparent absorption of 3.54 per cent. for dry air, and Magnus, with a nearly similar tube 1 meter long, got 2.46 per cent., concerning which Tyndall says: "Professor Magnus himself finds that the quantity of [radiant] heat transmitted through his unblackened tube is 26 times that which passes through his blackened one where the oblique radiation is cut off. In the case therefore of the naked tube, the flux of [radiant] heat sent down by the heated glass plate adjacent to the lamp, to its fellow at the other end, and likewise the [radiant] heat sent directly from the lamp to the same plate are greatly superior to what they are in the case of the blackened tube. The plate adjacent to the pile becomes therefore more highly heated, and as its chilling is approximately proportionate to the difference of temperature between it and the cold air, the withdrawal of heat will be greatest when the tube is unblackened within. * * * It is, I submit, not a case of absorption, but of direct chilling by the cold air." (*Contributions to Molec. Phys.*, pp. 419–420.)

> The third column of this table is calculated on the assumption that the absorption is proportional to the quantity of vapor in the tube, and the agreement of the calculated and observed results show this to be the case, within the limits of the experiment. It can not be supposed that effects so regular as these, and agreeing so completely with those obtained with small quantities of other vapors, and even with small quantities of the permanent gases, can be due to the condensation of the vapor on the interior surface. When, moreover, 5 inches of air were in the tube, less than one-sixth of the vapor necessary to saturate the space was present. The dryest day would make no approach to this dryness. Condensation under these circumstances is impossible, and more especially a condensation which should destroy, by its action upon the inner reflector quantities of [radiant] heat so accurately proportional to the quantities of matter present. (*Heat Considered as a Mode of Motion*, Am. Ed., pp. 405–406, 1869.)

In this quotation the air is said to have been humid, and yet, when reduced to a pressure of one-sixth of an atmosphere, to have contained "less than one-sixth of the vapor necessary to saturate the space." But if the air was anywhere near saturation at the ordinary pressure, it must have been supersaturated when reduced to a pressure of 5 inches, a fact which was perfectly well known to Tyndall, since he has described it on page 46 of the same work. I can only reconcile these statements by supposing that either Tyndall inadvertently overlooked the increase of relative humidity in air at reduced pressure, when writing this passage, or else that the description of the air as "humid" is very misleading; and I submit that the case is not quite so axiomatic as its author maintained, and that precipitation of liquid water on the inner walls of the tube at low pressures, if we take the first horn of the dilemma, may have diminished the reflecting power of the polished walls, while the lessening of the vapor contents at the same time would render the air more transmissive, giving a certain degree of compensation which is not incompatible with an increment of vaporous absorption by no means proportional to the air pressure.

On page 404 (*Heat as a Mode of Motion*) we read:

> The air of the laboratory was dried and purified until its absorption fell below unity; this purified air was then led through a U-tube filled with fragments of perfectly clean glass moistened with distilled water. Its neutrality, when dry, showed that all prejudicial substances had been removed from it and in passing through the U-tube it could take up nothing but the pure vapor of water. The vapor thus carried into the experimental tube produced an action ninety times greater than that of the air which carried it.

Tyndall has pointed out (*Contributions*, p. 387) that merely letting dry air bubble through cold water is not a perfect means of moistening it, but passage through U-tubes filled with wet glass is an effectual method of producing saturated air. The moistening described on page 404, *Heat as a Mode of Motion*, is not explicitly stated to apply to the conditions of the experiments with "humid" air on page 405; but in the *Contributions* (p. 411) it is stated the amount of aqueous vapor capable of being taken up by air at a temperature of 15° C., produced an absorbtion forty times that of air; and again (p. 412), we read: "It is with this common outer air, and not with air artificially saturated with moisture that I find the absorption of aqueous vapor to be fifty or sixty times that of the air in which it is diffused." Numerical values depend upon absolute quantities of vapor and these upon temperatures and concomitant details which are provokingly infrequent in Tyndall's memoirs, but from these supplementary statements one would infer that the humid air which gave an absorption of 98 in the table already quoted, must have been very nearly saturated, and that the measures at low pressures are open to criticism. Since, however, the experiments of Aitken show that air which is free from dust may be supersaturated without precipitation, I do not mean to assert that the precipitation did necessarily occur.

Abandoning tubes, Tyndall tried the method of displacing the free air between a cube of boiling water and the thermopile, alternately by air dried by fresh chloride of calcium and by air moistened by passing through a cylinder filled with fragments of quartz moistened with distilled water (*Heat as a Mode of Motion*, p. 407), obtaining a differential deflection of about 15°, corresponding (by p. 403, *loc. cit.*) to an aqueous absorption of about 2 per cent. (Temperature not mentioned.)

Hoorweg (*Pogg. Ann.*, Bd. 155, S. 385–402, 1875) repeated this experiment. No difference as great as 0.2 per cent. could be found at first between the absorption of dry and moist air, as exercised upon radiation from a Leslie's tube. The transverse dimensions of the air blast are not explicitely stated, but probably the air issued from a narrow jet. He then repeated the experiment with a moistener 50 cm. long and 9 cm. broad, obtaining for the absorption of moist air 1.7 per cent. (temperature 9° C.); and finally with a moistener 100 cm. long and 9 cm. broad, the source being a black copper plate heated by a Bunsen burner, he obtained, with an air temperature of 7°.5 C., an absorption of 2 per cent. by moist air, which might perhaps be doubled by substituting a source at 100° C.

I fail to see the cogency of some of the remarks in this paper. The final conclusion in regard to aqueous absorption is stated by this author as follows:

> From this I believe that 100 meters of ordinary air are still not by a long way in condition to produce the results which Tyndall already obtained from 10 feet, namely that 10 per cent. of the entering rays would be absorbed.

In regard to this statement, I can only say that its truth or falsity depends upon what is to be understood by "ordinary air." The temperature and humidity of what would commonly be considered as ordinary air vary so widely with the locality and the season, that without numerical definition of water contents such an assertion is too loose to be of any value. Tyndall's statement,* criticized in this passage, is drawn up in the same undefined way and is equally devoid of meaning, unless interpreted by other passages.

Dr. H. Buff (*Pogg. Ann.*, Bd. 158, S. 177-213, 1876) used an apparatus patterned after that of Magnus (*Pogg. Ann.*, Bd. 112, S. 531; *Phil. Mag.* (4), vol. 22, p. 85, 1861), but with a few alterations which Dr. Buff considered improvements. In fact, results were obtained which differed from those of Magnus, and indicated the source of some of his errors which had already been explained by Tyndall. Dr. Buff, however, appeared to think that he had overcome these errors, whereas it is evident that the method as conducted by both Magnus and Buff is unsound.

Instead of the glass-walled vessel to hold hot water which was used by Magnus, Buff had a vessel of sheet brass, polished on the bottom, and radiating downward upon a thermopile. Double side walls, stuffed with cotton wool, prevented rapid cooling. The metal vessel rested air-tight on a glass cylinder 20 cm. high and 7.5 cm. wide, which, in turn, was made air-tight on the plate of an air-pump. The thermopile of iron and german-silver wire, beaten out to a breadth of 12.5 mm. and soldered, was 23 mm. below the heating surface. In the first experiments the air was dried by passing it slowly through a 40-cm. tube of fused chloride of calcium. It is evident that the heating effect observed was a complex of convection, conduction, and radiation from a variety of sources. The maximum deflection, which was attained after a lapse of fourteen to twenty-two minutes, was due mainly to slow heating of the glass cylinder by conduction, and to the convection and radiation started by the resulting disposition of heated walls. The effect continued for thirty minutes, although the temperature of the hot water meanwhile had fallen continuously.

Dr. Buff having obtained, as he imagined, a transmission of 47.7 per cent. from 4.5 cm. of dry air, next increased his layer of air to 10 cm. The results were not such as to meet his expectations. "The absorptive power of air, instead of proportionately increasing, as I had supposed," he says, "seemed to decrease from the 50 per cent. previously observed to 20 and even 15 per cent." Yet notwithstanding this most improbable result, his confidence in the accuracy of his method and its interpretation (which differed in no important respect from that of Magnus) remained unshaken, while Tyndall's was branded as "unreliable," and these measures of Magnus and Buff have been repeatedly quoted as authoritative, in spite of their complete overthrow by Tyndall.

Blackening the bottom of Buff's brass vessel containing the hot water increased the deflections "but feebly, though the radiating power of the source of heat must have been 6 or 7 times greater than previously;" a result which proves that only a minute part of the observed effect can have been due to the radiation of the blackened brass, and which consequently demonstrates that the large variations observed were at any rate not due to absorption of radiation by the inclosed gases.

Only one other point in this paper requires mention, namely, the assertion that a plate of rock-salt, 0.3 cm. thick, absorbs 40 per cent. of the radiation from a vessel of hot water, and that the thermochrose of rock-salt and dry air are similar,* Buff maintaining that Tyndall found no absorption by air because his rock-salt plates had already sifted out the rays for which air is opaque. Professor Tyndall, in his reply (*Proc. Royal Soc. London*, vol. 30, p. 10, Dec., 1879), points out that he had already (see *Heat as a Mode of Motion*, p. 399) tried the experiment of bringing the naked face of his thermopile "within one-twentieth of an inch of [the] terminal plate of rock-salt. There was not the slightest alteration of the previously obtained result. Dry air, as before, behaved like a vacuum." The course of the radiation was here through a succession of vacuum, salt, vacuum (or dry air at pleasure), salt, and one-twentieth inch of normal air to the pile. There was little probability that so thin a layer of air as one-twentieth inch could sift out and totally remove any appreciable amount of a special class of rays; and Melloni's measurement, which made the transmission of a plate of rock-salt, 0.26 cm. thick, as great as 92.3 per cent. of the total radiation, almost all of the loss being due, not to absorption, but to nonselective surface reflection, might well have been deemed sufficient to prove the fallacy of Buff's suggestion that a few cm. of air or a small fraction of a cm. of rock-salt can totally remove a large percentage of the radiation; but to put the matter beyond all possible doubt, Tyndall constructed a new apparatus (*loc. cit.*, fig 1, p. 16) placing the thermopile in a chamber filled with hydrogen, protecting against hydrogen convection currents and radiation from side walls by diaphragms, and introducing a central variable chamber containing dry air, in which the thickness of the air layer could be varied from zero, when the inclosing rock-salt plates were in contact, to 3 inches, "which exceeds by more than 50 per cent. the thickness of the layer to which Professor Buff ascribes an absorption of 50 or 60 per cent." "Repeated experiments with this apparatus proved the absorption of the layer of dry air in the chamber to be *nil*."

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* "Regarding the earth as a source of heat no doubt at least 10 per cent. of its [radiant] heat is intercepted within 10 feet of the surface." (*Heat as a Mode of Motion*, p. 404.) It is to be borne in mind that this refers especially to radiation from a surface which is commonly moist and that such radiation through nearly saturated surface layers of air may be especially obstructed by aqueous vapor. (See *Contributions*, p. 395, and this bulletin, p. 90 to 105.)

The supposition of an identical absorption by rock-salt and air was then tested by comparing the transmission of a thick plate of rock-salt in vacuum with its transmission in air. There was no sensible difference. There is consequently no similarity in the thermochrose of air and rock-salt.

Finally, Tyndall shows that Buff's method, although defective "even when every care is bestowed upon it," may be improved. "A glass cylinder, 12 inches long and 2¾ inches in diameter, is mounted on the plate of an air-pump. On it is placed a tin vessel with a brass bottom, intended to contain the water which warms the bottom or source of heat. A thermopile is mounted on the air-pump plate on which the cylinder stands, one of its faces being presented to the bottom of the tin vessel. The conical reflector is abandoned, a piece of tubing, blackened within, and intended to cut off the radiation from the sides of the vessel, being pushed over the pile. Instead of bringing brass and glass into direct contact, as in the apparatus of Professor Buff, a washer of nonconducting india rubber, an inch and an eighth in thickness, separates the one from the other. There is no chilling by cold water, and the distance of the pile from the source renders it difficult for heat to pass by convection from the one to the other." With this apparatus, instead of finding olefiant gas more diathermant than air, as Buff had done, Tyndall obtained an absorption of 33 per cent. from a depth of 11 inches of olefiant gas, while air and hydrogen did not differ appreciably from a vacuum in their readiness of transmission. The results agree with Tyndall's earlier measures obtained by other methods.

It might be supposed that such a complete exposure of the fallacy of Magnus' method, both in its original form and as modified by Professor Buff, would forever settle the questions at issue; and that Buff's further statement that he, like Magnus, found no difference between the absorption of dry and moist air would be taken for what it is worth, namely, nothing at all; but such statements as those quoted from Ferrel, made six years after this crushing rejoinder, show that old errors die hard.

Prof. W. M. Davis, in his *Elementary Meteorology* (p. 145, Boston, 1894), says:

> The action of water vapor on insolation and terrestrial radiation has been much discussed. Some have regarded it as diathermanous to insolation, but relatively opaque to terrestrial radiation, and have therefore attributed to it a controlling influence in determining the temperature of the atmosphere. More careful experiments have, however, shown that water in the truly vaporous state is as diathermanous as pure dry air to terrestrial radiation; and that it is only water in the liquid state that exerts a strong control over radiation from the earth. This appears to be confirmed by observations on the diurnal range of temperature under varying conditions of humidity. If the

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* It will be shown subsequently (p. 114) that there is an analogy between the radiant powers of rock-salt and dry air, but not identity.

temperature of the air is well above saturation, the range is relatively strong; if near saturation, the range is diminished, even though no visible clouding of the sky occurs; if a thin hazy cloud is formed, the range is greatly reduced.

The experiments which have been interpreted in favor of the diathermancy of water-vapor have been refuted long ago, and Professor Davis, since the publication of his book, has given evidence that he no longer adheres to the erroneous doctrine there enunciated. (See his "Absorption of Terrestrial Radiation by the Atmosphere," *Science*, N. S. Vol. 2, p. 485, Oct. 11, 1895.) The diminution of the daily range of temperature with a clear sky, as saturation approaches, is to be attributed partly to a change in the quality of aqueous absorption, but also to the increase of water-vapor and its ascent to exceptional heights in the atmosphere in considerable quantity, whereby the escape of surface radiation is impeded by the strong aqueous absorption of the infra-red rays, especially for those between 5μ and 8μ, not far from the point where the maximum energy in the radiation from bodies at ordinary temperatures resides. The presence of large masses of water-vapor in the upper air may not always be indicated by high relative humidity at the surface, any more than by clouds, but it is evidenced by the strengthening of the rain-band, as seen in the spectroscope, as well as by the diminution of the diurnal range of temperature; and after heavy rainfall has depleted the upper air of moisture, the direct rays of the sun are intensified, and to a still greater degree the loss of heat by radiation from the earth's surface, so that the change of temperature between day and night reaches its greatest value, and at the same time the rain-band fades out, showing that it is the withdrawal of the invisible veil of water-vapor which has increased both radiation and daily range. The statement on page 32 of Professor Davis' book that "water vapor is, like clear air, a poor absorber of nearly all kinds of waves," and the doubt which is cast upon the theory that the atmosphere is a trap which allows solar rays to enter more freely than surface rays are permitted to escape, are both overthrown by the experimental demonstration of the efficacy of aqueous vapor as an absorbent of infra-red rays.

Prof. Thomas Preston in his *Theory of Heat* (p. 485, London, 1894) says in introducing the experiments of Lecher and Pernter (published in 1880): "But these new investigations, instead of settling the question in dispute between Tyndall and Magnus as to the comparative absorptions of dry and moist air, place the whole matter in a state of greater uncertainty. For whereas Tyndall found an exceedingly low absorption for dry and a high absorption for moist air, while Magnus found the same absorption for both, and that tolerably high, the results of the experiments of Lecher and Pernter show practically no absorption for either; or, in other words, both dry and moist air act as a vacuum toward radiant heat." These and numerous other less explicit statements in current scientific literature show that even down to the present day the question of the action of aqueous vapor upon telluric radiation is still regarded by many as an open one.

I proceed to the discussion of the last-named observations, which contain some puzzling but not inexplicable features. Lecher and Pernter (*Sitzb. der k. Akad. der Wiss. zu Wien*, July, 1880; *Phil. Mag.* (5), vol. 11, p. 1, Jan., 1881) by substituting a thin horizontal plate of lampblacked copper brought suddenly to 100° C. by a jet of steam, in place of the arched dome of glass heated by hot water in the original apparatus of Magnus, succeeded in shortening the time of exposure and diminishing the convection until they were able to confirm Tyndall's observation of the sensibly perfect transmission of radiation by dry air. But with a layer of 31 cm. of air they could detect no difference between the absorption of moist air and dry. Magnus' galvanometer and thermopile were too insensitive to measure this difference, even if his arrangement had been free from its other defects; but Lecher and Pernter's instruments apparently had the requisite delicacy, and we must seek elsewhere for the cause of their failure.

The face of the thermopile was covered with lampblack, which is very hygroscopic, and likewise the bottom of the radiating vessel. Whenever this was heated in moist air and in a closed vessel, moisture was driven off from the coating of the radiator and probably deposited to a sufficient extent upon the blackened thermopile to largely compensate by the development of latent heat for the slight diminution of radiation by only a few inches of moist air, while the radiation of the hot vapor (diminished by aqueous absorption) was added to that of hot metal. The short time of exposure (90 sec.) diminished the influence of convection currents, but favored the inclusion of a transitory phenomenon, like the evaporation of hygroscopically imbibed moisture.

The importance which has been attributed to the observation makes it desirable to analyze it somewhat critically. Comparing measurements of the absorption of various gases and vapors by Lecher and Pernter with those made on the same substances by Tyndall, it will be seen that the differences between their results for the absorption exercised on the radiation from a blackened metal plate at 100° C. are too large to be neglected, and in the case of vapors the discrepancies are excessive. as the following table shows:

TABLE 53.

	Lecher and Pernter.				Tyndall.				
	Length.	Pressure.	Absorption.	t.	Length.	Pressure.	Absorption.	t.	(‡)
	cm.	*mm.*			*cm.*	*mm.*			
Chloroform, $CHCl_3$	31	70	0.0050	Temperature of source 100°.	126	13	*0.216	Source 100°.	
Ether, $(C_2H_5)_2O$	31	13	0.0504		126	13	*0.541		
Benzole, C_6H_6	31	42	0.0619		126	13	*0.345		
Ethylene, C_2H_4	31	751	0.4826		5	762	†0.328	Source 270°.	0.551
Carbon monoxide, CO	31	744	0.0660		5	762	†0.068		0.076
Carbon dioxide, CO_2	31	748	0.0810		5	762	†0.076		0.094

* *Heat as a Mode of Motion*, p. 441. (Conditions described p. 431.)

† *Contributions to Molecular Physics*, p. 170.

‡ Temperature of source 100° C. Masses of gas equivalent to those in the experiments of Lecher and Pernter.

To account for their discrepancies Professors Lecher and Pernter refer to observations of Regnault (*Mem. de l'Acad. Fr.*, t. 26). "Regnault has observed that the tension of vapors is less in vacuum than in a space filled with air, and he explains this as the result of condensation on the walls. This causes a diminution of the vapor tension, so that while in a vacuum compensation is instantly made by the liquid, in a space filled with air this requires time, and the full vapor tension is never reached."* Now, in the cases cited Tyndall employed an exhausted tube, into which his vapors were allowed to expand from a sample tube connected with a vapor flask, the vaporization being made "without the slightest ebullition" (*Contributions to Molec. Phys.*, p. 179), but since there were no special precautions to keep all parts of the vapor chambers at the same temperature, it is conceivable that, on the opening of the vapor flask into the sample tube, a portion of vapor condensed on the walls of the latter, and subsequently, when the lower valve was closed and the upper opened, this condensed liquid evaporated into the absorption tube. Thus there may have been a larger quantity of vapor present in the absorption tube than might have been expected from the temperature of evaporation. In this way we may explain the fact, commented on by Lecher and Pernter, that the pressure in the vapor flask, computed from Tyndall's data,

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* This statement hardly expresses the facts of the original observations which are contained in *Mémoires de l'Académie des Sciences de l'Institut Impérial de France*, t. 26, p. 700, Paris, 1862. Regnault found that the density of aqueous vapor, relatively to that of air, increases as the saturation point is approached.

Relative humidity.	Relative density of aqueous vapor.	Relative humidity.	Relative density of aqueous vapor.
Per cent.		*Per cent.*	
100	0.64693	87.0	0.62499
96.4	0.63849	73.3	0.62140
96.4	0.62786	30.2	0.62078

Regnault himself says (p. 701): "The experiments which have been made at temperatures very near those of saturation give densities larger [than the theoretic density], and the difference is so much the greater as we approach nearer saturation. I conclude from this that the density of the vapor of water, *in the vacuum and under feeble pressures*, may be calculated after the law of Mariotte and according to the theoretic density, provided the fraction of saturation does not surpass 0.8, but that this density increases notably toward the state of saturation. This last circumstance may be due to two causes: either the vapor of water experiences, really, an abnormal condensation on approaching the state of saturation, or else a part of the water remains condensed upon the glass walls and only takes the gaseous state when the interior vapor is far from saturation."

Lecher and Pernter ignore Regnault's first explanation that aqueous vapor becomes abnormally condensed on approaching the point of saturation, but it will be shown subsequently that this condensation is a fact.

approaches the boiling point of the volatile liquid in several instances, whereas the experiments were actually conducted at a much lower temperature. But, admitting the truth of this part of the criticism and the uncertainty of the vapor densities computed from the relative volumes of sample and absorption tubes, the argument does not apply to experiments (such as those quoted in Table 53) in which the vapor pressures, *measured by a manometer*, fell far short of those for saturation at the presumed temperature. Tyndall is, unfortunately, very seldom explicit in describing his conditions of experiment, but it may be inferred from some of his statements that the temperature of his apparatus was in general that of the apartment, and not far from 15° C., at which temperature, and under complete absence of air, it is improbable that there can have been any appreciable liquid films condensed from the vapors in question. Moreover, the point can be subjected to a much more severe test.

Tyndall, in his *Contributions* (p. 171), gives a series of measurements in which not the vapor pressure, but the thickness of a layer of air saturated with ether-vapor, was varied. Here, if the absorption had been due to a film of liquid ether condensed on the rock-salt plates, the mere variation in the distance between these plates could have had no effect upon the transmitted radiation. In the next table Tyndall's results are given in comparison with a series by Lecher and Pernter, in which, however, it is the pressure of the ether-vapor which has been varied. Whether it is permissible to make comparison under these circumstances will be considered presently. The temperature in Lecher and Pernter's experiment was 7°.4 C., which fixes the pressure attainable at the upper limit at a figure probably lower than Tyndall's; but since Tyndall's greatest depth of air and saturated ether-vapor was only one-sixth of that used by Lecher and Pernter, the latter ought still to have had the greater absorption; nevertheless, according to their determination, the absorption was actually less. In Table 54, l is the length of the absorbent column, p is the pressure of the ether-vapor, t is the fraction of radiation from a lampblack surface transmitted by the ethyl ether, x is the exponential coefficient of transmission in the formula,

$$t = e^{-mx}$$

where e is the Naperian base, and m is the mass of absorbent vapor in a column of unit section. Without further data no absolute comparison is possible, but since m is proportional to lp, and l in the one case is constant and equal to 31 cm., p being constant in the other case, and probably about 35 cm., or nearly the same, p and l may be taken respectively in place of m in a preliminary computation of a multiple, nx, differing only slightly from x.

TABLE 54.—*Ether-vapor.*

Tyndall.					Lecher and Pernter.				
l	p	lp	t	nx for 1 cm. l	l	p	lp	t	nx for 1 cm. p
cm.	*cm.*				*cm.*	*cm.*			
0.127	35 ?	4.45	0.979	0.1672	31	1.28	39.68	0.9496	0.0404
0.254	35 ?	8.89	0.954	0.1854	31	4.12	127.72	0.8737	0.0328
0.508	35 ?	17.78	0.913	0.1792	31	7.86	243.66	0.7794	0.0317
1.016	35 ?	35.56	0.857	0.1519	31	12.52	388.12	0.6924	0.0294
2.032	35 ?	71.12	0.790	0.1160	31	23.33	723.23	0.5859	0.0229
3.810	35 ?	133.35	0.654	0.1115					
5.080	35 ?	177.80	0.649	0.0851					

For equal masses of ether-vapor the absorption and the exponential coefficient are considerably larger in Tyndall's series than in that of Lecher and Pernter; but in both the value of x increases as the absorbent mass diminishes,* and in nearly the same ratio, Tyndall's rate being slightly the greater. Thus, Tyndall's measures show that with a variation of the mass in the ratio, 1:20.00, there is a change in x in the ratio, 1:0.4590, while Lecher and Pernter, for a mass change in the ratio, 1:18.23, have a variation of x in the ratio 1:0.5673. From the result of this test, I think it can not be denied that the absorption by a vapor measured by Tyndall is genuine. Lecher and Pernter have also been measuring an effect which depends on the amount of vapor

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*Lecher and Pernter say: "x always becomes *smaller* as the thickness of the layer becomes smaller," which is obviously erroneous.

present, and where their results deviate from those of Tyndall it is owing to the defects of their method. It seems to me that the capacity of lampblack for condensing vapors to the liquid state, and absorbing them in its pores, is partly* responsible for the apparent inactivity of aqueous vapor in Lecher and Pernter's experiments by the compensation already explained; and it is noteworthy that their deviations from Tyndall are greatest in the case of the more condensible vapors, while for the permanent gases there is approximate agreement, especially if the comparison be made between the absorption of equal masses† exercised on radiation from the same source. This has been done in the last column of Table 53 for the three permanent gases by interpolating values, for a pressure of 7.5 inches of mercury, from Tyndall's *Contributions to Molecular Physics*, Table XX, p. 37, for CO_2, and Table I, p. 22, for C_2H_4, assuming that the total radiation is represented by the mean of the values on pages 18 and 19, or 334 units.‡ The figures for CO are obtained in the same way from Table XIX, p. 36. The pressure selected§ is such as to give an absorbent mass nearly identical with that of Lecher and Pernter. The result indicates that, where the physical state remains unchanged, it is permissible to compare the effects of equivalent masses even under diverse conditions of pressure or, in other words, it is the number of molecules encountered in passing through a given gas which determines the absorption of radiation.

From certain discrepancies in the relative positions of absorbent vapors in Tyndall's lists Lecher and Pernter deduce a variation of some 30 per cent. between the results from black and from polished tubes, and conclude that the unconformities which Tyndall attributed to impurities in his substances are really due to the variable proportion in which the transmission through a film of liquid adhering to the walls and the direct transmission through vapor enter into the results, according as a reflecting or a nonreflecting tube is employed. The criticism, however, is hardly conclusive, especially since they found their remarks on some of Tyndall's earlier measures in which the probable error of observation was large.

Finally, while themselves recognizing that transmission must be expressed by an exponential formula,

$$t = e^{-mx}$$

in which, unless the radiation be homogeneous, x varies as a complex function of m (the absorbent mass), any constant exponential coefficient being inapplicable to cases of absorption where particular rays are constantly dropping out, because totally extinguished, the authors fail to apply their knowledge where it is peculiarly needed, namely, in treating Violle's comparison of solar radiation at the top and bottom of Mount Blanc. They rightly conclude that the absorption of 16 per cent. exercised on the solar rays by a layer equivalent to 2,428 meters of air at normal pressure, and having a pressure of water-vapor of 5.3 mm. at the bottom, must have been largely due to the aqueous absorption; but, applying an erroneous formula, they then deduce a mean

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* It is evident that if the explanation given here is correct the numerical result must also depend in part upon the dimensions of the apparatus.

† Tyndall (*Heat as a Mode of Motion*, p. 433–435) has given an argument which proves that equivalent absorbing masses must be used, if the relative absorptions of different liquids and vapors are to be compared.

‡ From the explanation of the calibration of the galvanometer (pp. 17–19), and from the values juxtaposed in Tyndall's Tables I, III, and elsewhere, it is evident that the quantities labeled "absorption per 100" are not percentages, but absorptions stated in terms of forces, corresponding to galvanometer deflections, as read from a curve of calibration.

§ The values for the interpolation curve, in the case of carbon dioxide (4-foot layer, temperature of source 100° C., *loc. cit.*, p. 15), follow :

Pressure.	Absorption (obs.).	Absorption (interpolated).	Pressure.	Absorption (obs.).	Absorption (interpolated).
Inches.	*Per cent.*	*Per cent.*	*Inches.*	*Per cent.*	*Per cent.*
0.5	1.50	1.8	3.0	6.53	5.8
1.0	2.25	3.0	3.5	7.34	6.3
1.5	3.14	3.8	5.0	7.49	7.8
2.0	4.19	4.5	10.0	10.78	11.3
2.5	5.33	5.2	15.0	14.37	13.9

absorption of 0.007 per cent. by 1 meter of air of the given humidity and for sunshine, and compare this with Tyndall's absorption of radiation from a low-temperature source by a fresh layer of moist air, leaving the inference that this measurement—several hundred times greater than that computed on their assumption—must necessarily be wrong. This reasoning is quite inadmissible. In sunshine the rays absorbable by water form but a small part of the total radiation, while in the low-temperature sources employed by Tyndall they constitute the larger part. Besides this, the principal part of the absorption is exercised by the first few meters of moist air or their equivalent. It is perfectly safe to say that even at the summit of Mount Blanc an amount of aqueous vapor had already been traversed many times exceeding that in Tyndall's meter or thereabouts of moist air, and that a large part of the rays for which aqueous vapor is especially opaque and whose absorption was measured by Tyndall had already been sifted out. The reasoning by which Professors Lecher and Pernter support their failure to detect any absorption from moist air is, therefore, not justified.

Tyndall's last contribution to this subject is a paper on "The action of free molecules on radiant heat and its conversion thereby into sound" (*Phil. Mag.* (5), vol. 13, pp. 435–462, and 480–526, May and June, 1882). It contains a variety of incidental results which have a bearing on questions which have arisen in connection with the present research. The beginning of the paper gives an excellent historical summary of the Tyndall-Magnus controversy. On pages 455–456 we read concerning Magnus' experimental determination of the radiation from heated gases passed through a hot tube 15 mm. in diameter, bent up at the end, so that the vertical current ascended 400 mm. in front of the pile:

> When dry air was sent through this tube the deflection produced was three divisions of a scale; when air which had passed through water at a temperature of 15° C. was sent through the tube the deflection rose to 5 div.; when the water was warmed to 60° or 80° F. the deflection was 20 div.; and when the water boiled the deflection was 100 div. In this last experiment, however, a mist appeared, so that, as urged at the time, the radiation could not be said to have been purely from vapor. In the other case no mist was visible, but it was nevertheless concluded that the 20-div. deflection was due to the formation of mist at the boundary of the ascending current.

Tyndall concludes that the first deflection came—

> Not from dry air, but from the adjacent aqueous vapor which had been warmed by the dry air.
>
> That the deflection in the second experiment was small is not surprising. The radiation which could reach the pile from a jet of air only 15 mm. in diameter, and containing such moisture as could be taken up at 15° C., must have been extremely small under any circumstances. But in the present case even this small radiation was diminished by the passage of the [radiant] heat through 400 mm. of undried air. I should demur [says Tyndall] to the explanation of the third experiment and question the warrant to imagine a mist which could not be seen. Even the fourth experiment where mist was visible, yielded, I doubt not, a mixed result, part of the effect, and probably the smallest part, being due to the mist, and part of it to the vapor.

On pages 483–484 Tyndall refers to his own experiments on the transmission of a parallel beam of radiation from a rock-salt lens, described in his *Contributions* (p. 394), and says that the tube was rough brass, tarnished, and that the heating of the tube from air dynamically heated by compression, and from the partial condensation of vapor on the walls of the tube when the air was moist, produced a small radiation from its inner surface which disturbed the result. Hence in his new apparatus the interior of the tube was silvered and polished.

The absorptions measured by Tyndall are greater when the source is a slowly vibrating or low-temperature one, except in the case of absorption by carbon dioxide; but if the apparatus could be made sensitive enough to work with a very low-temperature source of radiation whose spectral maximum should be at a longer wave-length than the region of especial absorption, the result found for carbon dioxide would, no doubt, be the general one.

The radiation from a hydrogen flame proceeds principally from highly heated vapor of water and its absorption by 38 inches (96.5 cm.) of air at 60° F., saturated with moisture and containing an amount of water-vapor equivalent to a liquid layer 0.001 271 cm. deep, was found to be 10.7 per cent., while dry air produced no measurable absorption.

The thin liquid films produced by condensation of vapors on rock-salt plates when the concentrated vapors were allowed to flow over a plate placed in the path of the radiant beam were found to have no effect on transmission, unless, as in breathing on a plate, the film amounted to a visible wetting; but if the plate was put in contact with the pile the liberation of latent heat in the act of condensing from vapor to liquid produced powerful deflections.

The assumption that absorption depends upon the mass of the absorbent material traversed by the rays, and therefore is constant if the density of a vapor varies inversely as its depth, has appeared probable. To test the assumption further, Tyndall had two tubes whose lengths were as 3.5 to 1 and measured the percentage absorptions of ether-vapor, $(C_2H_5)_2O$, at inverse pressures.

TABLE 55.

Radiant source.	*Inches.*	*Inches.*		*Per cent.*
A dull lime light	$l_1=38.0$ $l_2=10.8$	$p_1=1.0$ $p_2=3.5$	lp 38	$a=30.3$ 30.0
	38.0 10.8	2.0 7.0	lp 76	38.8 38.5
Brighter lime light	38.0 10.8	1.0 3.5	lp 38	22.3 22.5
	38.0 10.8	2.0 7.0	lp 76	29.5 30.0
Brightest lime light	38.0 10.8	1.0 3.5	lp 38	18.4 18.8
	38.0 10.8	2.0 7.0	lp 76	25.7 25.6

The assumption of constant absorption of radiation from a source of constant temperature by an absorbent of constant mass is verified in this case, the physical state remaining unchanged.

The question whether the absorption of a given mass of material will remain constant when its state changes from the liquid to the vaporous condition demands separate treatment. Tyndall's answer for ethyl ether is contained in the following paired values:

Radiant source.		Absorption. Per cent.
Lime light with mirror	Ether vapor " liquid	32.4 32.9
" " " rock-salt lens	" vapor " liquid	33.3 33.3
Incandescent platinum with rock-salt lens	" vapor " liquid	66.7 67.2
The same on another occasion	" vapor " liquid	71.0 70.0

In like manner hydride of amyl (source of radiation not stated) gave equal absorptions of 51 per cent. in the two states. It is, of course, impossible to assert from these few observations that a like identity of liquid and vaporous absorption will hold good for other substances, although Tyndall's opinion was to the contrary,* and I shall show later that it does not hold true for water.

The experiments which give the title to the paper and introduce a novel method follow. By interrupting a convergent beam concentrated on a small bulb containing a vapor, employing for this purpose a toothed wheel revolved with such rapidity as to give the number of pulsations which evoked the resonance of the bulb, Tyndall found that the heat, instantaneously absorbed and radiated by the vapor, produced alternate expansion and contraction, giving a musical note whose intensity was proportioned to the combined absorbent and radiative power, as well as to the difficulty with which the substance volatilizes. The expansion could also be made evident upon a manometer. When radiation from a lime light was concentrated by a mirror upon a cylindrical vessel 4 inches long and 3 inches wide, with rock-salt end plates, the following water pressures were obtained on the manometer, according to the contents of the vessel:

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* In regard to the equality of liquid and vaporous absorption Tyndall says (p. 500): "A general law of molecular physics is, I apprehend, here illustrated."

	mm.
Chloroform, CH_3Cl	350
Aldehyde, C_2H_4O	325
Olefiant gas, C_2H_4	315
Ethyl ether, $(C_2H_5)_2O$	300
Nitrous oxide, N_2O	198
Marsh gas, CH_4	164
Carbon dioxide, CO_2	144
Carbon monoxide, CO	116
Oxygen, O_2	5
Hydrogen, H_2	5
Nitrogen, N_2	5
Dry air	5
Humid air, at 50° C	130

Although a few of the more absorbent of these substances, such as nitrous oxide and marsh gas, may exist as barely perceptible traces in the Earth's atmosphere, and carbon dioxide in larger proportion, the interest of this series to the meteorologist of course centers in the absorption of moist air relatively to that of dry air. The numbers, however, do not coincide with the relative absorbent values, being modified by the radiant powers of the substances, but as it is precisely this combination of radiative and absorbent qualities which determines the thermal state of the atmosphere, these relations are significant. In alluding to their meteorological bearing Professor Tyndall remarks (p. 516):

> The radiant power of air being practically *nil*, it retains for a considerable time the warmth imparted to it during the day, while when it is dry the rays from the surface of the earth pass unimpeded through it. Hence the relative refrigeration of the surface [at night and in dry weather].

The radiant power of dry air is underrated by Tyndall here and elsewhere,* but the general accuracy of his analysis of the atmospheric thermal mechanism remains unimpaired.

If the exact equivalence in absorption by equal masses of a substance in the liquid and in the vaporous states had been as firmly established as Tyndall imagined, his measures of the absorption of liquid water (*Heat as a Mode of Motion*, p. 430) could be utilized in connection with the atmospheric problem. The observations, which were made on radiation from a plantinum spiral raised to a bright red heat by an electric current, follow:

TABLE 56.

Thickness of liquid water.		Absorption.
Inches.	*cm.*	*Per cent.*
0.02	0.05	80.7
0.04	0.10	86.1
0.07	0.18	88.8
0.14	0.36	91.0
0.27	0.69	91.0

For comparison of absorption by water in the vaporous condition, the following values of the absorption by an air column, nearly 100 meters long, with varying humidity, have been taken from a treatise on the Moon's radiation, which includes some subsidiary researches on atmospheric absorption ("The Temperature of the Moon, from researches made at the Allegheny Observatory," by S. P. Langley, assisted by F. W. Very. *National Acad. of Sci.*, vol. 4, part 2, 3d Memoir, p. 186, Washington, 1889). In the last column I have deducted 2.5 per cent. from the original numbers for the absorption of carbon dioxide.

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* The small expansions of dry air and its chief constituents, nitrogen and oxygen, are attributed by Tyndall to a warming of the apparatus and to expansion of the gas by heat communicated to it by convection, rather than to heating by direct absorption of radiation by the gas; but, as in the case of dynamic heating, no sufficient reason is given for rejecting these smallest readings.

TABLE 57.

Relative humidity.	Equivalent depth of liquid water.	Absorption.
Per cent.	*cm.*	*Per cent.*
53	0.096	12.1
60	0.151	19.3
61.5	0.166	21.8
82	0.205	30.4

Plotting the observations with depths of precipitable water for abscissæ and absorptions for ordinates, it will be seen that the curve (fig. 13) departs slightly from a straight line, and more as

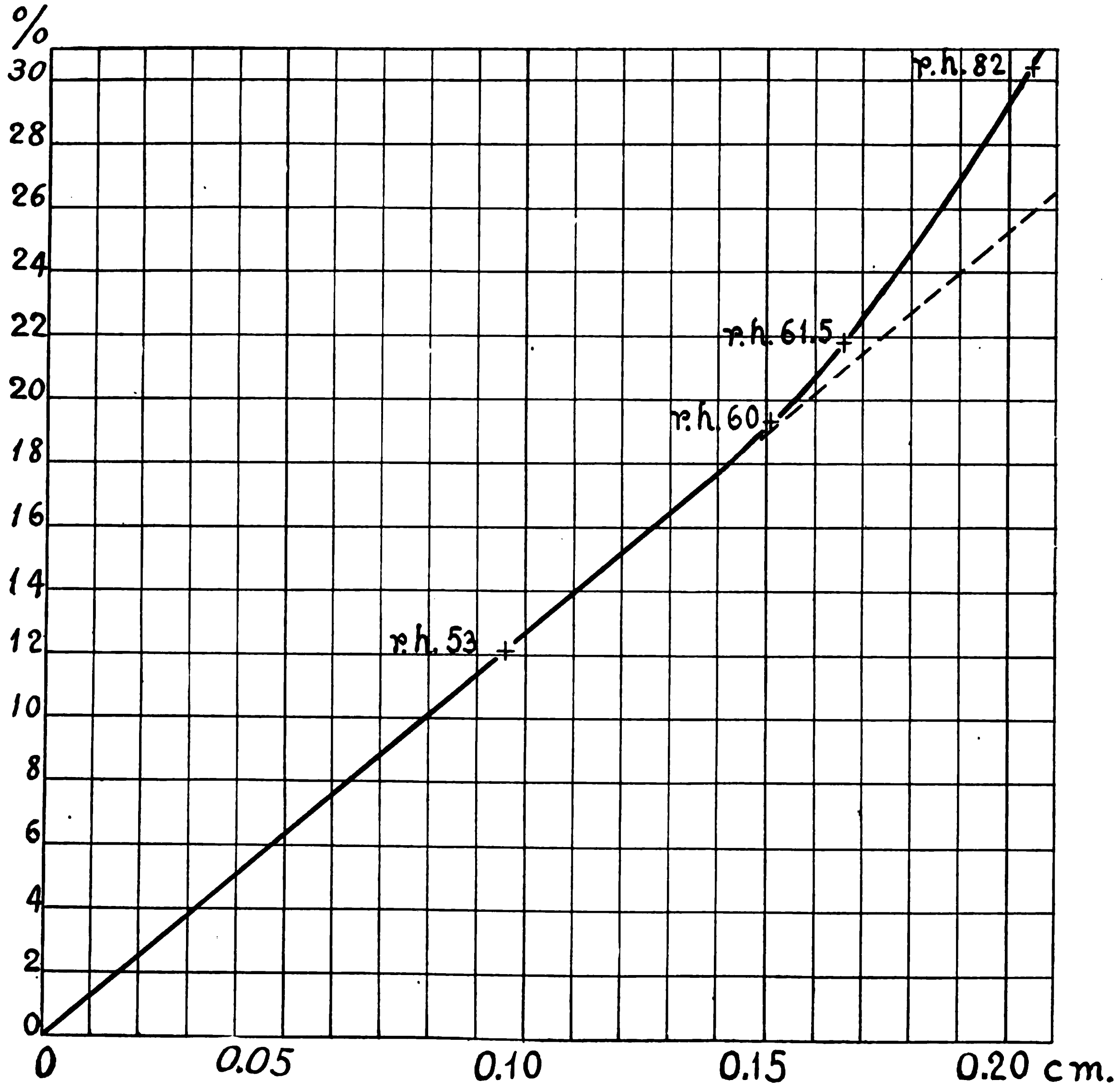

Fig. 13

the relative humidity increases, at least for relative humidities above 60 per cent. I infer that for an equivalent depth of 0.2 cm. of liquid water, for which an absorption of 28.8 per cent. is indicated, a reduction of 3.6 per cent. should be made to allow for an increment of absorption dependent upon greater relative humidity, the remaining absorption of 25.2 per cent. being due to normal water-vapor, plus an unknown but evidently very small correction for the effect of dry air.

For the equivalent depth of 0.18 cm. the absorption of water-vapor is 22.6 per cent., which may be compared with Tyndall's third observation (Table 56), whence it appears that for this amount of water the liquid absorption is four times the vaporous; but the rate of absorptive increase with growing depth is very different for the two states, and for an equivalent depth of one-half millimeter we have vaporous aqueous absorption, 6.2 per cent.; liquid aqueous absorption, 80.7 per cent., the liquid absorption being thirteen times greater than the vaporous.

No allowance is made here for any change produced by differences in the radiant source; but I shall now develop a method by which we may be independent of the temperature of the source. By combining spectral energy-curves and curves of absorption for homogeneous rays, we may deduce the total absorption for any case which can be given.

The following measurements of the distribution of energy in the spectrum of a blackened radiator filled with boiling water, and at a distance of 110 meters, are taken from page 186 of the memoir on the temperature of the Moon, already cited. The barometer stood at 739 mm., and the mean dew-point was + 12°.7 C., corresponding to 0.122 cm. of precipitable water. The deviations are those of a rock-salt prism whose angle (p. 132 *loc. cit.*) was "always very near 60°." The transformation factor, for reducing the galvanometer deflections to those of a normal spectrum, are taken from my paper "Further considerations in regard to laws of radiation" (*Astrophysical Journ.*, vol. 4, p. 43, June, 1896), and the wave-lengths are from Rubens' dispersion curve adopted in the same paper.

TABLE 58.—*Spectral energy-curves through water-vapor* (*radiant source, 99° C.*).

Minimum deviation (rock-salt.)	Wave-length.	Prismatic deflection.	Transformation factor.	Normal deflection.
°	μ			
39¼	3.10	31.3	.305	9.5
39	4.26	40.0	.364	14.6
38¾	5.22	48.8	.432	21.1
38½	6.03	28.4	.491	13.9
38¼	6.76	30.2	.549	16.6
38	7.41	42.6	.599	25.5
37¾	8.01	52.0	.647	33.6
37½	8.59	55.7	.691	38.5
37¼	9.11	62.0	.733	45.4
37	9.60	50.0	.772	38.6
36½	10.45	48.0	.839	40.3
36	11.2	42.0	.898	37.7
35½	11.85	33.2	.949	31.5
35	12.4	27.2	.991	27.0

Radiations of shorter wave-length than about 2μ are inappreciable in the spectrum of a body at the boiling point compared with one at the freezing point of water, and I have omitted such, assuming them to have been due either to reflected solar rays or to errors of observation. As the aperture for admitting radiation from the distant radiator, whose area was over 1 sq. m., also permitted wind to blow upon the measuring instruments, some irregularities are due to this cause; but the great depression between 5μ and 9μ, in fig. 14, where the normal ordinates in the last column of Table 58 are plotted, occupies the position of the great absorption-band of aqueous vapor and must be attributed to it.

Table 59 contains a spectral energy-curve observed with a fluorite prism by Paschen through 33 cm. of aqueous vapor at 100° C., corresponding to a layer of 0.0194 cm. of precipitable water. (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 3, heft 1, 1894.)

TABLE 59.—*Absorption by steam.*

Minimum deviation (fluorite).		Wave-length.	Radiation unabsorbed.	Radiation after absorption.	Transmission.	Absorption.
°	′	μ			*Per cent.*	*Per cent.*
28	46.5	5	99	74	74.7	25.3
28	16	5.5	76	16	21.1	78.9
27	41.5	6	56	5	9.0	91.0
27	5.5	6.5	41	3	7.3	92.7
26	25.5	7	30.5	6	19.7	80.3
25	40	7.5	21	15	71.4	28.6
24	52	8	14.5	13.5	93.1	6.9
24	1	8.5	7.5	7.5	100	0

The measured radiations are not given in this paper, and the values, corresponding to ether-waves differing in length by half a micron, have been read from the curves. The source of radiation was a hot sheet-iron cylinder over an Argand burner. The absorbent vapor was contained in a cylindrical metal tube 4 or 5 cm. in diameter, closed by end plates of thinnest copper, in which were open slits "of such dimensions that no rays reflected from the inner walls of the tube could reach the bolometer, but only such radiation as had passed directly through the gas layer in the tube. In this way all disturbance by 'adhesion of vapor,' etc., was excluded. A slender metal tube was screwed into the middle of the tube. This served to convey the gas under investigation in a slow but steady stream through the tube. In this way there was interposed a flowing layer of gas, of dimensions not exactly known, but very constant." (*Loc. cit.*, p. 4.) These measures are not available to as great wave-lengths as those made with a rock-salt prism, because

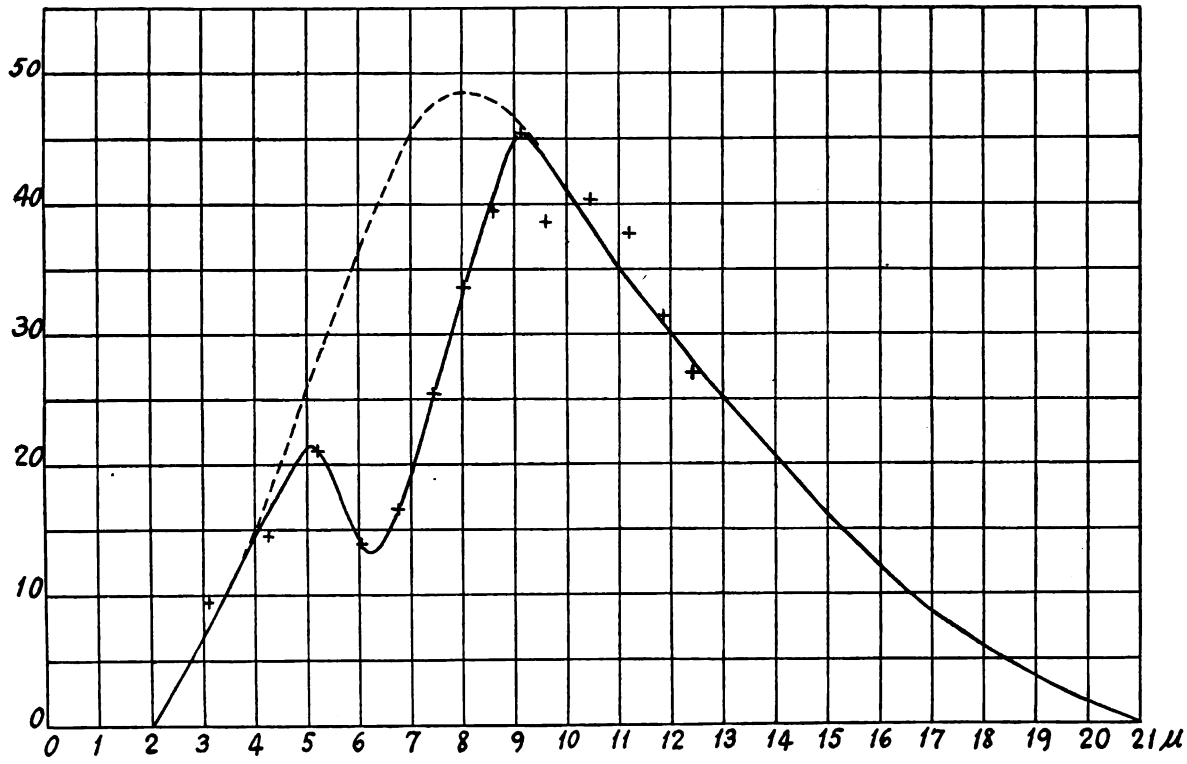

Fig. 14

Great water-vapor absorption-band. (Equivalent liquid = 0.122 cm.). Energy-curve of normal spectrum, reduced from rock-salt prismatic spectrum.

the absorption of fluorite nearly obliterates the radiation in the extreme infra-red spectrum where water-vapor begins to recover transmissive power.

Completing the missing portion of the energy-curve in fig. 14, as in the upper broken line, by the aid of spectral measures on a near radiator at the same temperature in dry weather, and adjusting the areas so as to give the same absorption (15.3 per cent.) which the curve in fig. 13 indicates for a depth of 0.122 cm. of precipitable water, the following radiant energies and percentages of absorption are obtained:

TABLE 60.—*Absorption by aqueous vapor.*

Wave-length.	Radiation unabsorbed.	Radiation after absorption.	Percentage transmitted.	Absorption.		
				0.1220 cm.[*]	0.0194 cm.[†]	0.0041 cm.[‡]
μ				*Per cent.*	*Per cent.*	*Per cent.*
5	26.0	21.3	81.9	18.1	25.3	5
5.5	31.2	19.0	60.9	39.1	78.9	40
6	36.4	14.0	38.5	61.5	91.0	68
6.5	41.6	14.0	33.7	66.3	92.7	70
7	45.6	20.0	43.9	56.1	80.3	47
7.5	48.0	26.8	55.8	44.2	28.6	20
8	48.5	32.2	66.4	33.6	7.9	14
8.5	47.6	39.2	82.4	17.6	0	5 (?)

[*] Absorption by water vapor in 110 meters of air at ordinary summer temperature, equivalent to 0.1220 cm. of liquid water.

[†] Absorption by 33 cm. of steam at 100° C., equivalent to 0.0194 cm. of liquid water. (Paschen, *Wied. Ann.*, as above, Table 59.)

[‡] Absorption by 7 cm. of steam at 100° C., equivalent to 0.0041 cm. of liquid water. (Paschen, *Wied. Ann.*, Bd. 52, Taf. II, fig. 1, curve 1 *c*, in which ordinates are percentages of absorption.)

For comparison two series of absorption values for steam, deduced from curves given by Professor Paschen, are included in the last two columns of Table 60. These are not obtained by direct measurement, but from a comparison of the curve of observation after absorption with a restoration by estimation of the curve before absorption. In regard to the restoration, obtained by drawing a continuous curve tangent to the shoulders on either side of the band, Paschen says (*Wied. Ann.*, Bd. 51, S. 11) that it "has thus too low rather than too high ordinates," and in consequence the indicated absorption is too small. This especially affects the estimates of absorption of the longer waves from 7.5 μ to 9 μ, where, the energy being very small in the fluorite spectrum, a comparatively slight change in the curve will produce a large alteration in the estimated absorption. The effect of this error is less noticeable with a source of radiation at a high temperature, such as was used by Paschen, but applied to observations on a low-temperature source, these small absorption values from 7.5 μ to 9 μ will give a restored curve of unabsorbed radiation having a depression at the maximum, which is inadmissible. The larger values of absorption are therefore to be preferred at the borders of the band, at least on the side of greater wave-length.

A further comparison of these results shows that a short column of concentrated, or saturated vapor absorbs more powerfully than an equal amount largely diluted with air, and further from the point of saturation. The absorption of a layer of saturated steam, 7 cm. deep (Table 60, Series 3) containing 0.0041 cm. of precipitable water, undiluted, exercises as great an absorption as 0.1220 cm. of precipitable water distributed as unsaturated vapor through 11,000 cm. of air. The quantity of vapor is here 30 times as great, the dilution 1,571 times as great in case 1 (Table 60) as in case 3. I have shown, however, that in the free air, where the dilutions are not widely different, the absorption is nearly proportional to the vapor contents, at least up to a depth of 100 meters.

A more extensive comparison may be made. I have found that a layer of water, 40 cm. thick, is almost absolutely impervious to solar infra-red radiation beyond wave-length 1.0 μ. No such absorption occurs with the most humid air as the sun approaches the horizon, although the absolute amount of water in a vaporous form, interposed in the path of the rays, must often be even greater than that contained in a liquid layer 40 cm. thick. Hence from the result of this test, made for us in nature on a grand scale, we have conclusive evidence that the selective absorption of vaporous water is not identical with that of liquid water, but that the former is comparatively permeable to infra-red radiations. Nevertheless, the general form of the absorption curve in the infra-red spectrum, as to its coarsest details, or broad groups of absorption-bands, and their relative intensities is very similar in the two cases.

Passing to the absorption-spectrum of liquid water, I have measured the ordinates in the spectral energy-curves for a fluorite prism which Paschen has given (*Wied Ann.*, Bd. 52, 1894, Taf. II, fig. 2, curves 1 to 4), in which a blackened platinum strip at 450° C.[*] was the radiant source. These readings have been divided by the ordinates with empty cell to obtain the corresponding percentage transmissions which are given in the next table.

TABLE 61.—*Absorption by liquid water.*

	Wave-length.	2μ	2.5μ	3μ	3.5μ	4μ	4.5μ	5μ	5.5μ	6μ	6.5μ	7μ	7.5μ	8μ	8.5μ
	Min. deviation..	30° 47′	30° 34′	30° 18′	29° 59′	29° 38′	29° 14′	28° 47′	28° 16′	27° 42′	27° 6′	26° 26′	25° 40′	24° 52′	24° 1′
WATER.															
	cm.														
Radiation.	0.0000	374	507	607	556	443	339	262	194	133	101	86	63	38	18
	0.0015	350	373	58	397	318	244	193	146	45	64	60	42	28	16
	0.0030	340	330	6	317	298	135	135	92	5	15	18	14	9	6
	0.0080	305	135	2	137	147	21	33	23	2					
Transmission.	.0015	93.6	73.6	9.6	71.4	71.8	72.0	73.7	75.3	33.8	63.4	69.8	66.7	73.7	88.9
	.0030	90.9	65.1	1.0	57.0	67.3	39.8	51.5	47.4	3.8	14.9	20.9	22.2	23.7	33.3
	.0080	81.6	26.6	0.3	24.6	33.2	6.2	12.6	11.9	1.5					
Absorption.	.0015	6.4	26.4	90.4	28.6	28.2	28.0	26.3	24.7	66.2	36.6	30.2	33.3	26.3	11.1
	.0030	9.1	34.9	99.0	43.0	32.7	60.2	48.5	52.6	96.2	85.1	79.1	77.8	76.3	66.7
	.0080	18.4	73.4	99.7	75.4	66.8	93.8	87.4	88.1	98.5					

The transmissions in this table, for the longer wave-lengths, have been multiplied by the ordinates of an unabsorbed normal spectral energy-curve at 100° C. to obtain the figures in the last three lines of Table 62, and the curves in fig. 15.

TABLE 62.—*Spectral energy-curves through liquid water (radiant source 100° C.).*

Wave-length.	5μ	5.5μ	6μ	6.5μ	7μ	7.5μ	8μ	8.5μ
WATER.								
cm.								
(1) 0.0000	26.0	31.2	36.4	41.6	45.6	48.0	48.5	47.6
(2) 0.0015	19.2	23.5	12.3	26.4	31.8	32.0	35.7	42.3
(3) 0.0030	13.4	14.8	1.4	6.2	9.5	10.7	11.5	15.2
(4) 0.0080	3.3	3.7	0.5	[0.5]	[2.2]	[2.8]	[1.0]	[2.0]

Measures made with a fluorite prism are not available for wave-lengths longer than 9 μ where the absorption of fluorite becomes large, but after this point aqueous absorption is comparatively insignificant until the region of the spectrum beyond 13 μ is reached. Solar and lunar radiations longer than 9 μ penetrate our atmosphere freely, even in moist summer weather, and Tyndall's observations (quoted in Table 56) show that 9 per cent. of the rays from platinum at a bright-red heat resist the absorption of liquid water. This remnant is distributed at irregular intervals through the spectrum. As the region beyond 12.5 μ comprises but a small fraction of the total energy from such a source, I shall assume, merely for the present purpose, that aqueous absorption ends at 12.5 μ, and as it is probable that certain feeble atmospheric absorption bands of greater wave-length than 9 μ are due to water-vapor, the curves are drawn undulating in the dotted portions supplied to complete the areas. The spectral region between 9 μ and 12 μ is very readily transmitted by water-vapor, but the limits of liquid absorption are wider. Aqueous absorption increases again gradually beyond 12 μ, and is perhaps the cause of the practical ending of the spectrum near 20 μ.

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[*] Subsequent measures by Paschen have indicated that the unabsorbed maximum in this curve has been displaced toward the shorter wave-lengths, owing to the imperfect absorption of the long waves by the bolometer, and that the maximum should be at 4 μ.

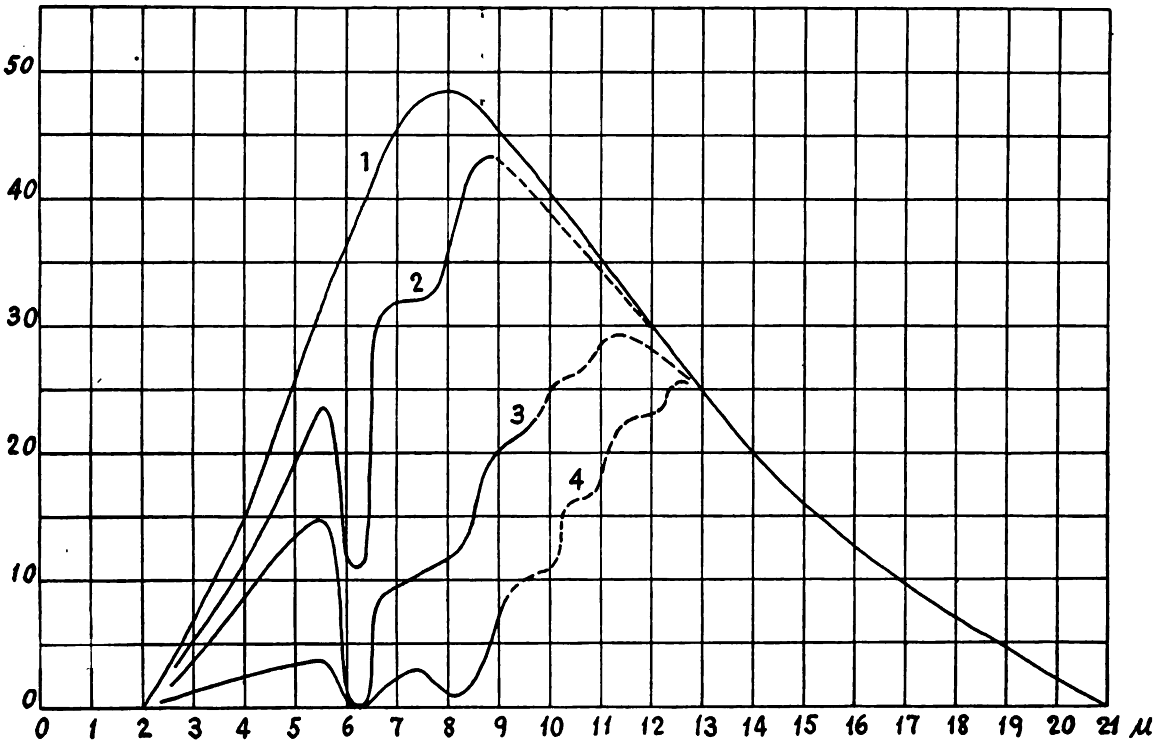


Fig. 15

Energy-curves of normal spectrum after absorption by liquid water.

Measuring the areas of the curves in fig. 15, and comparing 2, 3, and 4 successively with the unabsorbed energy-curve (1), the following transmissions of total radiation from a source at 100° C. are obtained:

TABLE 63.

Depth of liquid water.	Area of spectral energy curve.	Transmission of total radiation.	Absorption of total radiation.
cm.		*Per cent.*	*Per cent.*
(1) 0.0000	1.420	100.0	0
(2) 0.0015	1.016	71.5	28.5
(3) 0.0030	0.630	44.4	55.6
(4) 0.0080	0.341	24.0	76.0

If the aqueous absorption is exercised on radiation from a red-hot source, wave-lengths from 2μ to 5μ must be included, which is done in Table 64, the transmissions being obtained from Table 61, and combined with radiant values from a normal spectral energy-curve, taken from the reduction for a source estimated at 815° C., given in my paper, "Further considerations concerning laws of radiation" (*Astrophysical Journ.*, vol. 4, p. 43), in which, however, the temperature has probably been placed too high, since the position of the unabsorbed maximum more nearly agrees with that of the ideal black body at 450° C. (see footnote, p. 95; compare also my note in *Astroph. Journ.*, vol. 10, p. 208, Oct., 1899); but the discrepancy may arise in part from the use in the present case of a radiant which is not an ideal black body.

TABLE 64.—*Spectral energy-curves through liquid water (radiant source 815° C. ?).*

Wave-length.	2μ	2.5μ	3μ	3.5μ	4μ	4.5μ	5μ	6μ	7μ	8μ	9μ	10μ	15μ	20μ
WATER.														
cm.														
(1) 0.0000	40	67	160	187	193	190	182	154	117	84	60	42	16	5
(2) 0.0015	37.4	49.3	15.4	133.5	138.6	136.8	134.1	52.1	81.7	61.9				
(3) 0.0030	36.4	43.6	1.6	106.6	129.9	75.6	93.7	5.9	24.5	19.9				
(4) 0.0080	32.6	17.8	0.5	46.0	64.3	11.8	22.9	2.3						

These values are plotted in fig. 16. Three principal regions of large absorption are shown. The first, extending from 2.2μ to 3.7μ, with the minimum near 3μ, occupies the position of Langley's X and associated bands (χ_1 χ_2) in the solar spectrum. The second depression from 4.2μ to 5.2μ (minimum at 4.7μ) encroaches on the great carbon dioxide band, but does not seem to be as strongly developed in the vaporous absorption of water; neither does it appear in the absorption of 0.0015 cm. of liquid water, although quite well marked in the curve for 0.0030 cm. The third region is that of the great aqueous absorption band from 5.2μ to 7.0μ with a subordinate extension to 9μ, its deepest depression being at 6.1μ. The vaporous absorption differs in showing two minima, at 5.86μ and 6.51μ. A succession of smaller bands follows, the absorption of the liquid diminishing from 8μ to 12μ. In this region aqueous vapor has very free transmission, and the same is true of a liquid layer 0.0015 cm. thick.

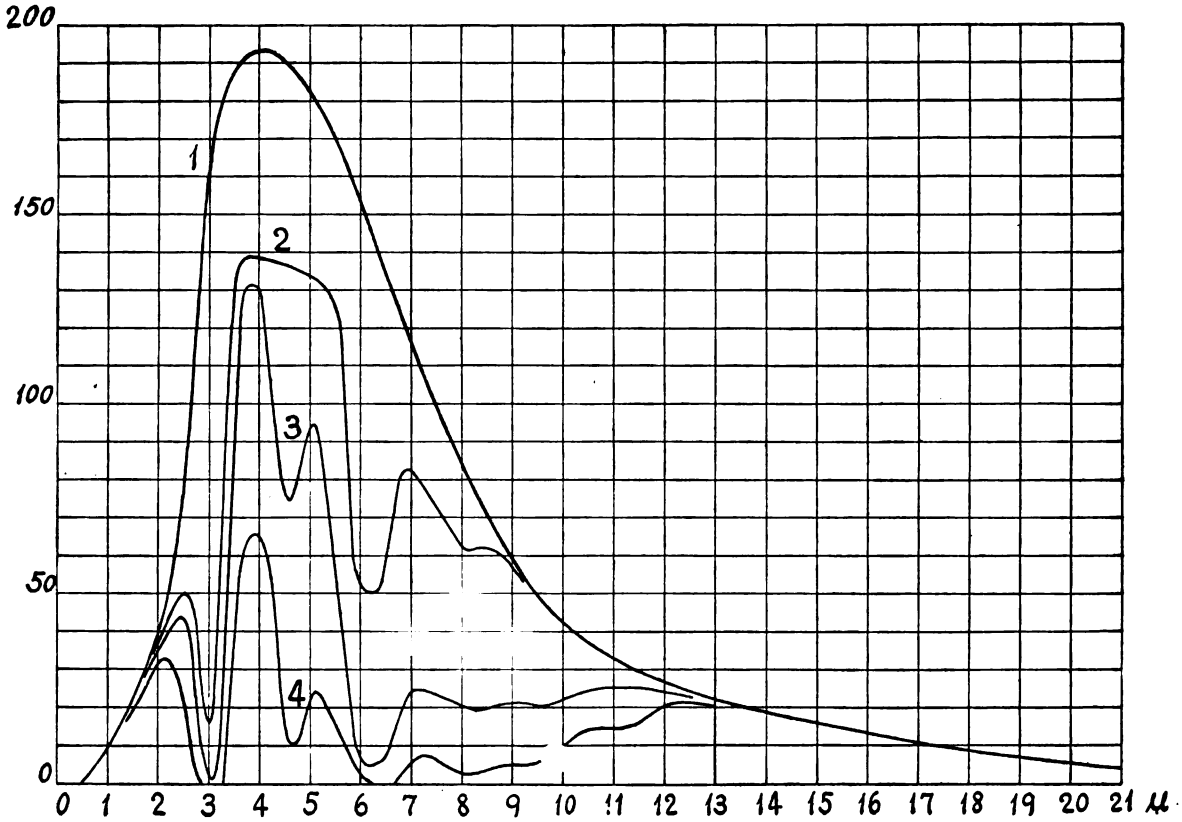


Fig. 16

Energy-curves of normal spectrum after absorption by liquid water.

Comparing areas in fig. 16 the following transmissions of total radiation from a source estimated at 815° C. are found:

TABLE 65.

	Depth of liquid water.	Area of spectral energy curve.	Transmission of total radiation.	Absorption of total radiation.
	cm.		*Per cent.*	*Per cent.*
(1)	0.0000	2.576	100	0
(2)	0.0015	2.175	84.4	15.6
(3)	0.0030	1.487	57.7	42.3
(4)	0.0080	1.015	39.4	60.6

Within the given limits of temperature (100° and 815° C.) the transmission for every thickness is greatest for the radiation from the hotter source, a result which is as old as the measurements of Melloni, but which is here presented no longer as an empirical fact, but as a piece of knowledge which may be rationally conceived and which can be applied deductively to a variety of special cases.

We are now in a position to assert confidently that so long as the physical state remains unchanged and the total aqueous absorption does not exceed 50 per cent. the increment of aqueous absorption is nearly proportional to the depth of the absorbing layer, but beyond this point the rate of increase in the absorption falls off very rapidly until finally further addition to the layer produces almost no effect.

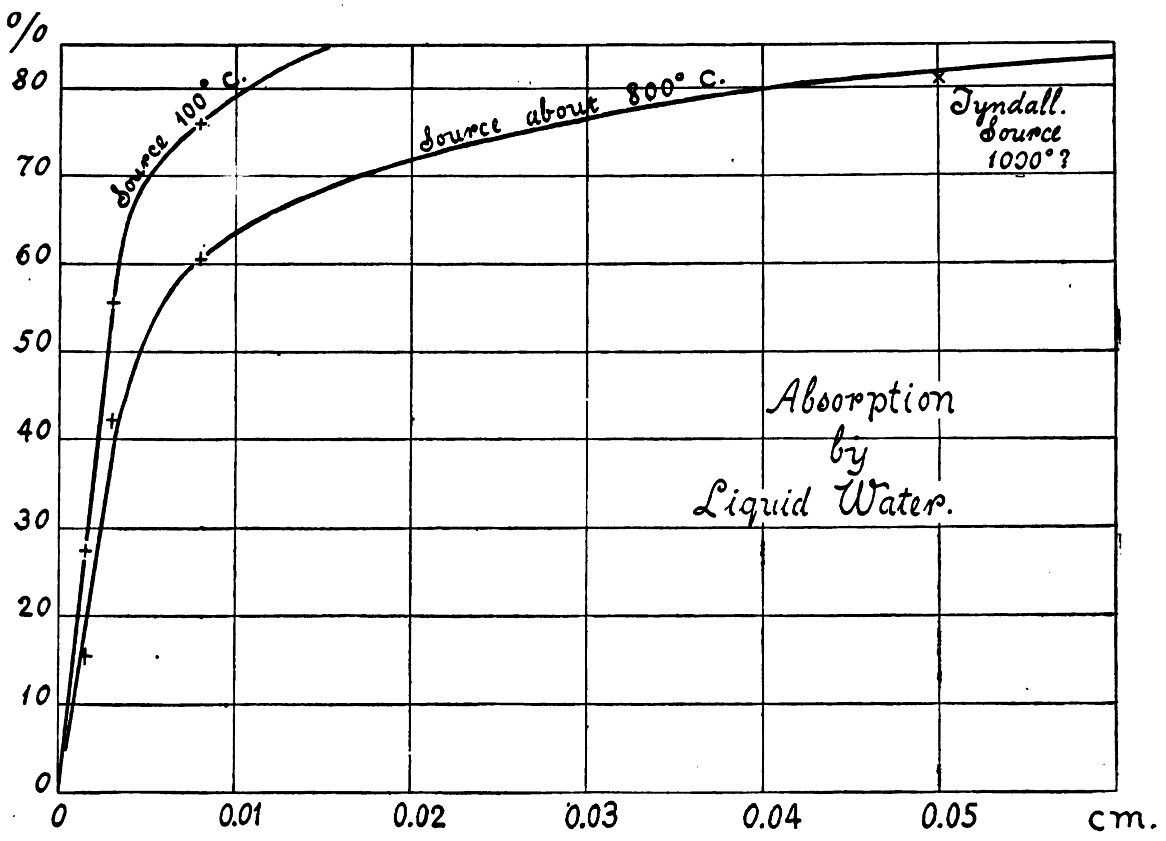


Fig. 17

Next, by comparing the curves in figs. 13 and 17, it can be stated that the absorption of total radiation by water-vapor in high dilution in the free air falls far below its absorption when condensed to the liquid state, but in a ratio which varies with the depth of the absorbent mass, as the following table shows:

Table 66.—*Aqueous absorption of total radiation* (*radiating body at 100°*).

Depth of precipitable water.	Absorption by liquid water.	Absorption by vapor in 100 m. air.	Ratio $\frac{\text{liquid absorp}^{n}}{\text{vapor absorp}^{n}}$.
cm.	*Per cent.*		
.001	19.5	0.125	156
.002	38.0	0.250	152
.003	55.5	0.375	148
.004	63.3	0.500	127
.005	67.9	0.625	109
.006	71.2	0.750	95
.007	73.8	0.875	84
.008	76.0	1.000	76
.009	78.0	1.125	69
.010	79.8	1.250	64

From this comparison it appears that with a radiating source at the boiling point of water, 10 microns of liquid water absorb 156 times as powerfully as the same amount of water distributed in the vaporous state through about 100 meters of air. We have seen that even an approach of the aqueous vapor to its condensation point increases its absorptive power (Table 57 and fig. 13). Paschen's result, already described (*ante*, p. 94), shows that saturated aqueous vapor at 100° C. exercises an intermediate absorption between that of the liquid and the invisible nonsaturated vapor of the atmosphere, 40 microns of liquid water absorbing 63 per cent. of radiation from a source at 100° C. (by Table 66), while the same quantity of water in the form of steam takes out about 15 per cent., and distributed as atmospheric vapor only one-half of 1 per cent. (by fig. 13 and Table 66).

The identity of absorption in the liquid and vaporous states which Tyndall found for ethyl ether and amyl hydride, presumably obtains only for those substances which do not change their molecular constitution in passing from one state to the other. The influence of molecular form upon absorption was, indeed, recognized by Tyndall, who says (*Contributions to Molecular Phys.*, p. 98):

> No coincidence between the vibrations of a radiating body and those of oxygen, hydrogen, or air could make any one of these substances a good absorber. They are physically incapacitated from communicating motion, and hence in an equal degree from accepting motion. The form of the atom [molecule?], therefore, or some other attribute than its period of oscillation [let us say, rather, some attribute on which that period depends], must enter into the question of absorption.

See also pages 102–105 (*loc. cit.*), where ozone is shown to absorb immensely more than oxygen. The atoms are here the same. It is the molecular form alone which has changed.

It is probable that some of the most important selective radiations of these elementary gases are of short wave-length and are not emitted until high temperatures are reached. We know that the linear absorption of cold oxygen in the visible spectrum is very feeble, requiring a long column of gas to show the A, B, and α groups of lines in the spectrum of a lime-light; but there is a region of great absorption in the extreme ultra-violet. Von Schumann finds that a layer of air 1mm. thick cuts off all rays beyond 0.175μ; and Liveing and Dewar (*Proc. R. Soc. London*, vol. 46, p. 222, 1889) have found that the absorption of 18 meters of oxygen in the ultra-violet is of the nature of a broad diffuse band, whose limits extend to greater wave-lengths on the less refrangible side as the pressure increases. At a pressure of 97 atmospheres, when the mass of oxygen in their tube was "rather greater than is contained in a vertical column of equal section of the Earth's atmosphere," the rays were completely absorbed to a wave-length of 0.2797μ. At 50 atmospheres the total absorption had its limit at 0.2696μ; and at 23 atmospheres the limit of extinction had receded to 0.2599μ.

Two kinds of bands appear in the absorption-spectrum of oxygen, in regard to which

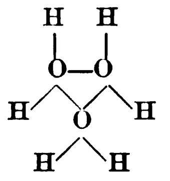
Professors Liveing and Dewar make some suggestions which are of interest in the present connection:

> The absorptions of the class to which A and B belong must be those which are most easily assumed by the diatomic molecules (O_2) of ordinary oxygen. * * * As for the other class of absorption, the diffuse bands, since they appear to have intensities proportional to the square of the density of the gas, they must depend on a change produced by compression. This may either be the formation of more complex molecules, as for example O_4, corresponding to the deviation from Boyle's law exhibited by oxygen gas, or it may be the constraint to which the molecules are subject during their encounters with one another. Increase of temperature would affect the former, tending to diminish the number of complex molecules formed at a given pressure, but would have no effect on the latter, for though the number of encounters of the molecules in a length of time would be greater the higher the temperature, yet so long as the volume was unaltered the ratio of the duration of an encounter to that of free motion would be sensibly unaltered. So far as any change due to temperature has been observed, it is that a rise of temperature slightly weakens the diffuse absorptions (*loc. cit.* pp. 227, 228).

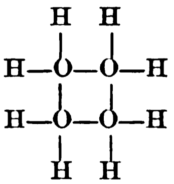
Consequently these observations favor the hypothesis that compression produces a limited number of complex and highly absorbent oxygen molecules which, even though few in number, are able to impress a peculiar character upon the spectrum.

Profs. W. Ramsay and J. Shields ("The molecular complexity of liquids," *Trans. Journ. Chem. Soc. London*, vol. 63, p. 1089, 1893), from their experiments on the surface tension of liquids as a function of the relative number of molecules per square centimeter of surface and the temperature, conclude that several molecules of water-vapor unite to form a complex molecule of liquid water; but ethyl oxide has the same molecule in the liquid as in the vaporous state. Regarding oxygen as tetravalent, the liquid molecules of water may be closed chains, *e. g.*:

$(H_2O)_3 =$



$(H_2O)_4 =$



At 60° C. the composition of the liquid molecule of water is $(H_2O)_3$, while at the temperature of maximum density most of the complex molecules are represented by the second formula.

The gradual formation of closed chains as the aqueous vapor approaches saturation,* must take place most readily if the molecules of vapor are not widely separated by diluting air. Meteorologists have often commented on the peculiarities of nearly saturated air, and some have conjectured that gaseous water exercises no appreciable absorption, and that the absorbent effects attributed to it are really due to a mist of liquid water, relative humidity being more important than vapor tension as an index of absorptive power. We have seen that gaseous water does produce a very potent influence of its own, but it seems to me to be demonstrated by what precedes that there is a remarkable increase in absorption by water at the critical point of incipient condensation, and as this point is somewhat closely approached. The suffocating sensations experienced in a very hot muggy atmosphere are attributable to the partial cessation of evaporation from skin and lungs, but the thermometric effects, such as the diminution of the daily range of temperature under a clear sky, which becomes very noticeable when the relative humidity is high, can be due only to strong absorption of the long-waved terrestrial radiations, and it is interesting to note that the difference between the absorption of liquid and vaporous water lies chiefly in the greater absorption of longer waves by the former. Professor Paschen says (*Wied. Ann.*, Bd. 51, S. 22, 1894):

> Liquid water has a very deep absorption-band which reaches from [fluorite minimum deviation] 29° 55′ [3.58μ] to 30° 40′ [2.29μ], and has its maximum at 30° 23′, 2.92μ [subsequently corrected to 2.84μ], while the corresponding band of the water-vapor at 100° extends from 30° 18′ [3.00μ] to 30° 40′ [2.29μ], and has its maximum at 30° 31′, 2.66μ [subsequently corrected to 2.58μ]. That of the liquid water begins consequently at the same place as the gaseous on the side of the short waves, but ends at longer waves. A maximum also appears in [the absorption of] liquid water at 27° 40′ [6.02μ]; for water-vapor at 100° its position is 27° 53′ [5.85μ]. * * * If we remember that the emission-maximum of the oxyhydrogen flame lies at 30° 26′ [2.75μ], we can indeed say that

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* Compare Regnault's observations cited, *ante*, p. 85.

liquid water absorbs the vibrations that the gaseous emits or absorbs. The liquid absorbs, however, in addition, such as belong to neighboring longer waves, and these indeed so much stronger that the absorption-maximum lies 3′ farther toward the long waves than the emission-maximum of the oxyhydrogen flame.

The spectral energy-curve of the oxyhydrogen flame, given by Paschen (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 6, 1894), shows, in addition to the emission-band just mentioned, which corresponds with the absorption-band of the solar spectrum called X by Langley, also the correlatives of the solar bands Ω and Ψ. The band X is partly due, and the band Y wholly due, to the absorption-bands of carbon dioxide, discovered by Knut Ångström. I quote Paschen's description of his identifications:

> Since Langley's bands Ψ, Ω, X, Y, etc., coincide within the errors of measurement with the absorption-bands determined by me, we may refer the given bands of the solar spectrum with great probability to the CO_2 and H_2O contained in our atmosphere. The wave-lengths of Langley's bands are: Ψ at 1.4μ, corresponding to the emission-band of H_2O at 1.4μ; Ω at 1.83μ, corresponding to an emission-band of H_2O at 1.83μ; $X = 2.64\mu$, corresponding to $H_2O = 2.66\mu$; Langley's band widens at low sun toward the longer waves. The new band arising at 2.94μ coincides with the absorption-maximum of liquid water which I find lying at 2.92μ. $Y = 4.6\mu$ corresponds to the CO_2 band at 4.63μ. From 5μ to 11μ Langley's solar spectrum is divided. Here lie the strong water-vapor absorptions (maxima at 7.1μ and 8.1μ). (*Loc. cit.*, p. 18.)

The last two wave-lengths were subsequently corrected after more accurate comparison of deviations from a fluorite prism and wave-lengths as given by a grating, becoming 5.86μ and 6.51μ. The limits of the great water band are also more nearly 5μ and 8μ, the correction affecting chiefly the wave-lengths above 5 microns. In this passage Dr. Paschen has misunderstood Langley's use of the word "maximum," which refers to an elevation in the energy-curve of the solar spectrum and not to the point of greatest absorption in a cold band. Langley (*Am. J. Sci.* (3), vol. 36, p. 403, 1888) distinctly says that 2.94μ is a subordinate maximum of the solar spectral energy-curve, and again he says (p. 404): "From 4.0μ to 4.5μ we have another region of almost complete absorption, followed by a maximum at 4.6μ." It appears probable that some of these numerical values will require further slight adjustment. Langley's original value for the center of Y, namely, 4.25μ, has since been confirmed by Paschen, who gives from his measures with a grating 4.245μ (*Wied. Ann.*, Bd. 52, S. 222).

The region of the solar spectrum from wave-length 2.3μ to 3.3μ is especially variable. Subordinate absorption-bands on the less refrangible side of X become apparently transposed in relative importance as the altitude of the sun above the horizon or the vapor-contents of the atmosphere change.

> Observations made during the winter indicate that the band at 2.64μ is, with a high sun, largely filled up, especially on the less refrangible side. At noon a subordinate maximum has been found within the low sun limits of this band at 2.94μ, and a second one at 2.80μ frequently accompanies it, producing subordinate minima at 2.89μ and 3.02μ. As the absorption increases with a sinking sun, these subordinate maxima disappear to a very great extent, that at 2.80μ being the first to vanish, as well as the quickest to grow, so that at noon, on a cold day, it not only surpasses the maximum at 2.94μ, but even begins to approach that at 3.20μ, while, when the sun's altitude is less than 10°, the nearly uniform part of the band extends from 2.45μ to 3.15μ without a break. (Langley, *Memoirs of the National Academy of Science*, vol. 4, 2d Mem., p. 167, 1887.)

The varying form of the spectral energy-curve is doubtless due to the complex linear composition of the bands, individual lines, or groups of lines, having very different rates of growth as the absorbent depth varies; and to a corresponding variation in the emission of the several lines composing a group, coupled perhaps with the effect of self-absorption of its own radiations by the outer layers of a gas or vapor, is to be attributed the change in the measured positions of infra-red bands, noted by Langley and abundantly confirmed by Paschen. Of the two principal centers of the great absorption-band of water-vapor, the longer at 6.51μ appears to expand to still greater wave-lengths and the shorter at 5.86μ to still shorter wave-lengths, or in either case away from the common center, as the mass of the absorbent increases; and Paschen shows that the same movement occurs in the maximum points of the emission-bands of water-vapor as the temperature rises. The following table is quoted from his paper (*Wied. Ann.*, Bd. 52, S. 215, 1894), with wave lengths approximately corrected by his latest measures of fluorite dispersion (*Wied. Ann.*, Bd. 53, S. 822).

TABLE 67.—*Emission-spectrum of water-vapor.*

Temperature.	Position of the highest point in—			
	Maximum I.		Maximum II.	
	Deviation.	Wave-length.	Deviation.	Wave-length.
	° ′	μ	° ′	μ
Oxyhydrogen flame			28 29	5.28
Bunsen flame, 1,470°	26 58	6.60	28 25.5	5.34
1,000°	27 0	6.57	28 23	5.38
600°, approximately,	27 2.7	6.54	28 11	5.58
100°	27 5.5	6.50	27 51.3	5.87
17° (vapor)	27 6.5	6.48	27 48	5.92
17° (liquid)			27 40	6.02

The relative strength of the maxima of the strongest emission-bands in the spectral energy-curve of water-vapor at different temperatures follows closely the relation between the corresponding intensities at the same wave-lengths and temperatures in the spectrum of a black body; and the absolute intensities are not far behind. This indicates that at these points the radiant power of a comparatively small mass of vapor is nearly perfect; but this can not be said of the borders of the bands, and we need not expect that any completely consistent rule should be followed in their variation. The bolometer covers several alternations of radiant or absorbent spectral lines and their intervals, giving us the sum of the series. If the lines broaden and the intervals fill up until the lines coalesce completely, the limits of perfect radiation or absorption widen, and if the band is one-sided, its center changes its position in the spectrum. So long as there is no disintegration of atomic groupings increased heat may bring out new lines and give greater complexity to the spectrum, changing the aspect of a group. Since the centers of several aqueous bands shift to longer waves as the temperature rises, their structure probably resembles that of the A and B groups of oxygen, in beginning with strong lines on the side of the short waves and gradually fading out in a long series of feebler and more widely separated lines on the side of the long waves. The shifting of the center of Maximum II (Table 67) is in the opposite direction, and is also more rapid than that of I. In II the relatively greater increase of radiations of short wave-length with rising temperature may assist, as suggested by Paschen, but only by aiding a process depending on structural detail of the band, which here fades out in the same direction as the shifting of the maximum ordinate in the spectral energy-curve of a black body. In I a similar greater increase of short than of long waves can not entirely overcome the structural shifting to the side of the long waves; and the same is true of the band *X*, while *Ω* and *Ψ*, situated in a part of the spectrum where the rate of increase of intensity with temperature varies rapidly with the wave-length at flame-temperatures, have the structural shifting toward long waves slightly overbalanced by the more general formal change, as is shown in the next table, also taken from Paschen's work (*Wied. Ann.*, Bd. 52, S. 226), the wave-lengths corrected as before.

TABLE 68.—*Emission-spectrum of water-vapor.*

Temperature:			°	′	μ
Oxyhydrogen flame	*X*	Deviation	30	26.0	λ = 2.75
Bunsen flame			30	25.5	2.77
Over 1,000°			30	26.0	2.75
500°			30	29	2.65
100°			30	30.8	2.59
Oxyhydrogen flame	*Ω*		30	52.0	1.78
Bunsen flame			30	51.5	1.81
Over 1,000°			30	51.0	1.84
Oxyhydrogen flame	*Ψ*		31	3	1.34
Bunsen flame			31	2	1.38
Over 1,000°			31	2	1.38

For the wave-lengths of the last three bands we need not depend on transformations from dispersion measures, since these maxima can be identified in the grating-spectrum of the Bunsen flame. Paschen's curve (*Wied. Ann.*, Bd. 50, Taf. IX, fig. 8) gives the following values:

(1) { Group Ψ extends from 1.33μ to 1.50μ.
Subordinate maxima, 1.35μ and 1.42μ; mean, 1.385μ.

(2) { Group Ω extends from 1.75μ to 2.10μ.
Subordinate maxima, 1.80μ, 1.86μ, and 1.97μ; mean, 1.877μ.

(3) { Group X extends from 2.42μ to 3.02μ.
Subordinate maxima, 2.51μ, 2.70μ, and 2.83μ; mean, 2.680μ.

In the absorption-bands of the solar spectrum, the deepest depression of Ω extends from 1.81μ to 1.87μ according to Langley ("Researches on solar heat," *Prof. Papers of the Sig. Serv.*, No. 15, p. 228, Washington, 1884), and the extension of the group on the side of the long waves is much feebler than in the emission-band of the Bunsen flame. The subordinate maximum of X at 2.83μ in the flame spectrum appears to agree with the minor band in the solar spectrum, called χ_1 by Langley, the wave-length of which was originally given as 2.89μ (*ante*, p. 101). That at 2.70μ agrees in position with one of the bands of CO_2.

Captain Abney and Lieutenant-Colonel Festing have photographed a continuous spectrum through several inches of water, getting the absorption-spectrum to a wave-length of 1μ ("Atmospheric absorption in the infra-red of the solar spectrum," *Proc. R. Soc. London*, vol. 35, p. 80, 1883). Three inches of liquid water give the following bands: (1) begins with a strong, sharp edge at 0.735μ and extends to 0.765μ, fading out thence on the side of the long waves, very gradually. Great A is included in its diffuse margin. (2) in like manner begins with a strong, sharp edge at 0.833μ, between Brewster's *X* and *Y*, and fades out gradully toward the long waves, the principal part of the band extending from 0.833μ to 0.875μ. The strong pair of lines, *X*, in the solar spectrum, due to calcium, wave-lengths 0.854μ and 0.866μ, is included in the diffuse margin. (3) is a very strong band between wave-lengths 0.942μ and 0.986μ, occupying nearly the same position as the bands in the solar spectrum, called $\rho\ \sigma\ \tau$ by Abney. It is bordered by hazy extensions and broadens to 0.88μ, when the depth of water is increased to 1 foot. These three bands are not composed of fine lines, but are diffuse, and they appear in photographs of the solar spectrum, superposed on groups of lines, and becoming very strong when the relative humidity approaches saturation. The authors say:

> Besides these linear absorptions, photographs taken on days of different atmospheric conditions show banded absorptions superposed over them. * * * On a fairly dry day the banded absorption is small, taking place principally between $\lambda 9420$ and $\lambda 9800$; a trace of absorption is also visible between $\lambda 8330$ and $\lambda 9420$. On a cold day, with a northeasterly wind blowing [this being for England the dry quarter], and also at a high altitude on a dry day, these absorptions nearly, if not quite, disappear. * * * When the air is nearly saturated with moisture, * * * except with very prolonged exposure, no trace of a spectrum below $\lambda 8330$ can be photographed. (*Loc. cit.*, pp. 80–81.)

Comparing these observations with those of Liveing and Dewar on the two kinds of oxygen bands, linear and diffuse, and with the facts adduced here which show that there is a very large increase in the absorptive power of aqueous vapor when nearly saturated, it seems probable that the diffuse bands of liquid water and of a saturated vapor are due to the complex aqueous molecules discovered by Ramsay and Shields, while the groups of fine lines in nearly the same positions in the spectrum belong to simpler molecules which no longer exist in the liquid state, but are present in variable proportion in the vapor, according to the temperature and the degree of saturation.

Abney and Festing in another paper ("The influence of water in the atmosphere on the solar spectrum," etc., *Proc. R. Soc. London*, vol. 35, p. 328, 1883) give spectral energy-curves for the crater of the positive carbon of an arc-light after absorption by various thicknesses of liquid water, obtaining evidence that nearly all of the great cold bands in the solar spectrum to 3μ are due to water. The liquid absorption-bands are, however, much more intense than the vaporous ones, and coalesce to form extensive regions of complete absorption. In addition to these curves, rough photographs of the solar spectrum to a wave-length of 2.2μ were taken on cold dry days, which confirm the presence of all of these water-bands and give their positions more accurately than the heat-measures made in the spectrum with a linear thermopile whose aperture was one-fiftieth of the length from the D-line to the end of the infra-red spectrum from a glass prism. In the following table these thermal measures (*loc. cit.*, p. 332) are exhibited as percentage-transmissions in the last three columns:

TABLE 69.—*Transmission of spectrum by liquid water.*

	Radiation through empty glass cell.	Deflection through—			Transmission by—		
		⅛ inch water.	1¾ inches water.	24 inches water.	⅛ inch water.	1¾ inches water.	24 inches water.
					Per cent.	*Per cent.*	*Per cent.*
At *D*-line in yellow	7.5	7.3	6.8	3.2	97	91	43
Maximum in orange-yellow	8.7	8.7	8.5	4.0	100	98	46
Orange band	10.0	9.2	8.8	3.7	92	88	37
Maximum in red	16.7	16.7	16.0	10.7	100	96	64
Red band (near *A*)	19.3	18.5	17.0	2.3	96	88	12
Maximum near *Y*	22.8	22.8	20.6	1.4	100	90	6
Band between *X* and *Y*	24.6	23.0	21.0	0.3	93	85	1
Maximum (Herschel's α)	25.4	24.7	22.0	0.0	97	87	
Band (Abney's $\rho\ \sigma\ \tau$)	27.7	21.5	5.3		78	19	
Maximum (Herschel's β)	30.0	26.3	10.0		88	33	
Band (Abney's Φ)	[26.7]	18.5	0.5		69	2	
Maximum (Herschel's γ)	[24.9]	19.0	7.0		76	28	
Band (Abney's Ψ)	18.5	0.7	0.0		4	0	
Maximum (Herschel's δ)	11.6	3.0			26		
Band (Langley's Ω)	[5.4]	0.0			0		
Maximum (Herschel's ε)	[2.9]	1.5			52		
Band (Langley's *X*)		0.0			0		

The extreme infra-red region of the spectrum, beyond the great water-band, has recently been explored by Prof. H. Rubens and E. Aschkinass (*Wied. Ann.*, Bd. 64, S. 584, 1898; translated in the *Astrophys. Journ.*, vol. 8, p. 176). The radiation from the mantle of a zirconium burner passing through a cast-iron tube 75 cm. long, "heated above 100° by four Bunsen burners beneath it," and fed with a permanent stream of aqueous vapor, was formed into a spectrum by a prism of sylvite, which at a wave-length of 18μ still transmitted "some 70 per cent., and at 20μ some 30 per cent., of the incident radiation." The general results are thus stated by the authors (*Astrophys. Journ.*, vol. 8, p. 190):

> Water-vapor shows only faint absorption in the spectral region between $\lambda = 9\mu$ and $\lambda = 11\mu$, as compared with shorter and longer waved parts of the infra-red. From this follows the minimum [emission] observed in the emission [curve of hot water-vapor] at $\lambda = 10.7\mu$. Beyond 11μ the absorption begins to increase and becomes almost total at $\lambda = 20\mu$, whereby the maximum observed in the emission [from hot water-vapor] at $\lambda = 13.1\mu$ is explained. [The transferring of the maximum from 20μ in absorption to 13μ in emission is about what might be expected from the rate of increase of the radiation of a black body with shortening wave-lengths, combined with the larger transmission of the shorter waves by sylvite in this part of the spectrum.] In the region between 11μ and 18μ, water-vapor possesses six conspicuous maxima of absorption, which have according to our observations the wave-lengths $\lambda = 11.6\mu$, 12.4μ, 13.4μ, 14.3μ, 15.7μ, and 17.5μ.

The intensities of absorption of these six bands are 10, 20, 28, 43, 63, and 88 per cent., respectively; while at 20μ, as stated, the absorption is nearly 100 per cent. Beyond this point, at wave-lengths 24.4μ, aqueous vapor exerts only a very slight absorption (Rubens and Nichols, *Phys. Rev.*, vol. 4, p. 322, 1897; also *Wied. Ann.*, Bd. 60, S. 418, 1897). Since air was not excluded from the apparatus, it is possible that the total absorption at 20μ may have some other origin (see p. 113).

It will be evident that the interrelations of aqueous absorption and radiation in terrestrial meteorology must be complex. The radiations of clouds, the sea, and to a considerable extent those of moist earth and vegetation do not differ much from the radiant emission of a solid black body whose spectral energy-curve has its maximum, at terrestrial temperatures, in the immediate vicinity of the chief aqueous absorption-bands. The depletion of radiation is especially great if the coincidence of maximum radiation and principal absorption is exact; but the position of the maximum of aqueous absorption in the spectrum varies with the amount of water and with its physical state. The position of the maximum of the unabsorbed energy-curve also varies with the temperature of the radiating body and of the surface to which it radiates. Thus there is room for a great variety of combinations.

The apparent absorption of a layer of heated vapor is a differential one, being the resultant of a series of operations made up of the sum of the original radiation of the body behind the vapor, minus the absorption exerted upon this radiation by the vapor, plus the emission of the vapor's own radiation, diminished by the absorption of the radiation from deeper vaporous layers by the vapor subsequently traversed. Since the vaporous emission varies with the temperature, the apparent absorption of the hot vapor likewise varies, except at temperatures too low for appreciable emission. This is very well shown in the series of absorption and emission curves for carbon dioxide at temperatures from 180° to 480°, given by Paschen (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 8, 1894). At the highest temperature the apparent absorption is almost nothing, the radiant emission by the hot gas having counteracted its absorption. I have already noted (*ante*, p. 53) that this observation may be used in constructing a curve of temperature and depth at which absorption exactly compensates radiation. Another point on such a curve is given by the present measures (*ante*, p. 54), which show that for a temperature of 126° C. the effective radiating depth of carbon dioxide is only a little over 3 feet, let us say 100 cm. Paschen's measurement gives the temperature of 480° C., corresponding to a depth of 7 cm.

ABSORPTION OF RADIATION BY CARBON DIOXIDE.

Prof. Knut Ångström (*Wied. Ann.*, Bd. 39, S. 306, 1890; see also the preceding article, beginning p. 267), quoting observations by Lecher which show that the solar rays, after sifting by an air-mass of three atmospheres, are almost entirely deprived of those ether-waves which are susceptible of absorption by a moderate depth (1.05 meters) of carbon dioxide, concludes that, since the mean quantity of this gas in the atmosphere is less than 0.02 per cent., corresponding to a vertical depth of less than 1.5 meters of CO_2, and in three atmospheres to less than 4.5 meters, the transmission by one meter of carbon dioxide, within the limits of the CO_2 absorption-bands, is between 20 and 30 per cent., because the transmission of these particular rays, after a preliminary sifting through 0.5 meters of CO_2, has been found to follow the simple exponential law:

$$i = I \times t^m,$$

where I is the initial intensity of the limited radiation, t the transmission by unit-mass, m the actual mass of carbon dioxide (measured as the depth in meters of CO_2 traversed by the rays), and i the resultant intensity after absorption, by which law this degree of transmissibility secures the extinction of these rays. The strength of the chief carbon dioxide band in the solar spectrum also appears to agree with what might be anticipated from the known absorbent mass of this gas in the Earth's atmosphere, and the assumption that carbon dioxide gas has a simple molecule under every degree of dilution and that its absorption depends entirely upon the mass of gas traversed, is warranted.

One other assumption, however, is less commendable. While such small transmissions as 20 to 30 per cent. are the rule in limited regions, or bands, in the infra-red, it is not permissible to apply them, as Ångström has done, to the entire infra-red of the solar spectrum, thereby raising the estimated solar constant to four small calories.* It must be understood that the absorption of 20 to 30 per cent. is the mean absorption of a series of bands which include special rays totally absorbed, as well as intermediate ones which go free.

Ångström's result indicates that about 4.5 meters of carbon dioxide is sufficient to almost completely cut off the radiations absorbable by this gas, and taken in conjunction with Keeler's observation (*Am. J. Sci.* (3), vol. 28, p. 196, Sept., 1884) that 3.4 meters of carbon dioxide absorb 35.8 per cent. of the radiation from a Bunsen burner flame, the two ought to give approximately the relative values of CO_2 and H_2O radiations from this flame whose spectrum is purely one of bands. We should anticipate from these facts that not over 40 per cent. of Bunsen flame radiation is due to carbon dioxide, the rest coming mainly from water-vapor. This differs somewhat from the relative areas of the sums of the respective maxima in Paschen's curve of energy in the spectrum of the Bunsen flame, but as the composition of ordinary illuminating gas is variable, some range in the aqueous component of flame-radiation must be expected from this cause; and, besides this, the temperature of the flame is not a constant quantity, while the relative radiations of the different components do not vary with the temperature according to the same law. Nevertheless, I believe that the chief cause of the discrepancy is the considerable absorption by the fluorite of Paschen's prism of those emission-bands of aqueous vapor which are of greater wave-length than those carbon dioxide bands which furnish the larger part of the emission at high temperatures. Separating the CO_2 and H_2O bands in Paschen's curve (*Wied. Ann.*, Taf. IX, fig. 6), I found the relative areas were:

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*The application of the method by which Ångström obtains this value leads to the absurd result that over 60 per cent. of the original solar radiation is contained in the spectral region occupied by the bands of carbon dioxide. The limits of these bands have now been ascertained, and it is certain that they do not cover a length of the solar spectrum possessing more than a small fraction of this proportion of total radiant energy.

$$CO_2 : H_2O = 115 : 107$$

Making allowance for fluorite absorption increases the proportion of aqueous radiation, and reverses the ratio. Hence less than half the radiation of the hot gases of the Bunsen flame is due to carbon dioxide.

The growth of the band-emission, as temperature rises, agrees so nearly with the rate of increase of the total radiation of carbon dioxide that another reason is added to Paschen's argument in favor of the absolute discontinuity of its spectrum. Zöllner and Wüllner having reached the conclusion that a gaseous layer of infinitely great depth would send out a continuous spectrum from the broadening of the lines, a conclusion which presupposes that emission and absorption are never zero for any wave-length, Paschen tested the hypothesis by observing the absorption of 33 cm. of carbon dioxide at the maximum in the spectrum of an incandescent lamp ($\lambda = 1.4\mu$), a point quite outside the special regions of absorption for this gas. No difference greater than one part in four thousand could be found between the absorption of air and CO_2 at this point. "It is improbable that such absorptions, if they were present, should be the same; it is more likely that both are zero. However, in consequence of the moisture of the air, a small and equal absorption may have been present every time." (*Wied. Ann.*, Bd. 51, S. 33.)

"The fact that CO_2 exerts an absorption which at any other spectral positions than those of its absorption-bands is zero within the limits of errors of observation stands in connection with another fact that the breadth of the absorption-bands in question does not grow with increasing depth of the layer." The breadth of the principal CO_2 absorption-band, at $\lambda = 4.25\mu$, remained unchanged when the thickness of the cold gas-layer was increased from 0.3 cm. to 33.0 cm., the absorption of the maximum meanwhile increasing from 55 to 90 per cent. "For line spectra it follows * * * that with increasing thickness of the gas-layer in emission the lines only become brighter, but, in general, can not spread themselves over the entire spectrum." (*Loc. cit.*, p. 34). This does not prevent the greatest variety as to strength and rates of growth in such spectral lines as those of water-vapor, but the carbon dioxide spectrum is much simpler. Besides the two bands discovered by Knut Ångström

(1) at 2.3μ to 3.0μ, maximum 2.7μ, and
(2) at 3.9μ to 4.7μ, maximum 4.25μ,

Rubens and Aschkinass have discovered a third strong band in the extreme infra-red. With a thickness of a little more than 20 cm. of CO_2, "the whole region of absorption is limited to the interval from 12.5μ to 16μ, with the maximum at 14.7μ. Aside from this region not the slightest absorption could be detected between 8μ and 20μ, even when the box was completely filled with carbon dioxide," giving a depth of 65 cm. (*Astrophys. Journ.*, vol. 8, p. 191, 1898.)

The absorption at different points in band (3) (*loc. cit.*, p. 189, fig. 9) is as follows:

[Source, zirconium burner—Absorption by 20 cm. + of CO_2.]

Wave length.	Absorption.	Wave-length.	Absorption.	Wave-length.	Absorption.
μ	*Per cent.*	μ	*Per cent.*	μ	*Per cent.*
12.5	1	14.0	28	15.0	70
13.0	4	14.5	67	15.5	30
13.5	10	14.7	75	16.0	2

The absorption at the center of band (2), according to Paschen (*Wied. Ann.*, Bd. 51, S. 9), amounted to 30 per cent. from the small trace of carbon dioxide in the air of the room. This was increased to 89 per cent. by the addition of a 7 cm. layer of the gas, but after this absorption was reached, further increase of the layer up to 33 cm. made little difference. At band (1) (*loc. cit.*, p. 10), an initial absorption of 10 to 20 per cent. by the air of the room was increased to about 30 per cent. by the 7 cm. layer, and to 43 per cent. by a layer of CO_2 33 cm. thick.

Owing to the very local distribution of the bands of carbon dioxide, the total amount of its absorption varies greatly with the temperature of the radiant source on whose emanations the absortion of the gas is exercised. Assuming that the absorption by a thickness of 1 inch of CO_2 at 30 inches pressure is identical with that of 48 inches of CO_2 at 0.625 inches pressure, we have from Tyndall's measures (*Contributions to Molec. Phys.*, pp. 37 and 170):

Temperature of source of radiation 100° C.; 1 inch of CO_2[*] absorbs 2.2 per cent.
" " " " 2 " " " 3.4 "
" " " 270° C.; 1 " " " 6.3 "
" " " " 2 " " " 7.6 "

Hence the absorption of radiation from the source at higher temperature is two to three times as great as for the radiation from the low-temperature source. The reason for this is seen on comparing the spectral energy-curves of the sources. The chief band of carbon dioxide ($\lambda = 4.25\mu$) falls near the maximum ordinate in the curve for 270°, but affects a relatively insignificant region of the spectrum of a body at 100° C. On the other hand, the chief absorption by water-vapor agrees more nearly in wave-length with the maximum of the source of lower temperature, whose radiation, in consequence, is relatively more depleted in passing through moist air than that of a hotter body.

From the figures just given we may infer that the amount of carbon dioxide in 100 meters of air at normal pressure absorbs about 2.5 per cent. of the radiation from a source at 100° C.

APPLICATION OF THE FOREGOING STUDY OF GASEOUS ABSORPTION TO THE RESULTS OF LABORATORY EXPERIMENTS.

We are now ready to correct the measured values of apparent gaseous radiation, obtained in Method C, by allowance for the modifications introduced by gaseous absorption.

By Table 48, p. 71, the apparent radiation of 141.8 cm. of carbon dioxide was:

At excess 50° C. $r = 93 \times (10)^{-9}$ radim
" " 80° C. 260 " "
" " 100° C. 482 " "

According to the data in the chapter on screens, the corresponding measured radiations of a screen of sooted copper (the initial temperature being 35° C.) were:

At excess 50° C. (358° absol. T.) $r = 1335 \times (10)^{-9}$ radim
" " 80° C. (388° absol. T.) 2321 " "
" " 100° C. (408° absol. T.) 3095 " "

From the curve (fig. 18), representing the absorption by carbon dioxide of radiation from sooted copper at 100° C., founded on the observations of Tyndall, already cited, it may be inferred that a 5-foot layer of CO_2 intercepts 18.4 per cent. of the rays. The corresponding absorptions for the sources at lower temperatures will be about 0.8 and 1.5 per cent. smaller, or 17.6 and 16.9 per cent., respectively. Hence the disk-radiation, in the extreme positions, was diminished as follows:

Depth.	Temperature-excess.	Disk-radiation absorbed by CO_2	and by rock-salt.
60 in.	50° C.	$1335 \times 10^{-9} \times 0.169 = 225.6 \times 10^{-9}$	169×10^{-9}
60 in.	80° C.	$2321 \times 10^{-9} \times 0.176 = 408.5 \times 10^{-9}$	306×10^{-9}
60 in.	100° C.	$3095 \times 10^{-9} \times 0.184 = 569.5 \times 10^{-9}$	427×10^{-9}

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[*] Compare *ante*, footnote on p. 87.

At the smallest distance (4¼ inches) the disk-radiation must have been diminished thus:

Depth.	Temperature-excess.	Disk-radiation absorbed by CO_2	and by rock-salt.
4¼ in.	50° C.	$1335 \times 10^{-9} \times 0.055 = 73.4 \times 10^{-9}$	55×10^{-9}
4¼ in.	80° C.	$2321 \times 10^{-9} \times 0.055 = 127.7 \times 10^{-9}$	96×10^{-9}
4¼ in.	100° C.	$3095 \times 10^{-9} \times 0.055 = 170.2 \times 10^{-9}$	128×19^{-9}

All of these radiations have suffered an absorption of about 25 per cent. by the rock-salt plate,* as given in the last columns for comparison with the measured radiations also absorbed to approximately the same extent. The observed apparent radiations of the gas must be increased by the differences of these numbers and further increased by the absorption of rock-salt.

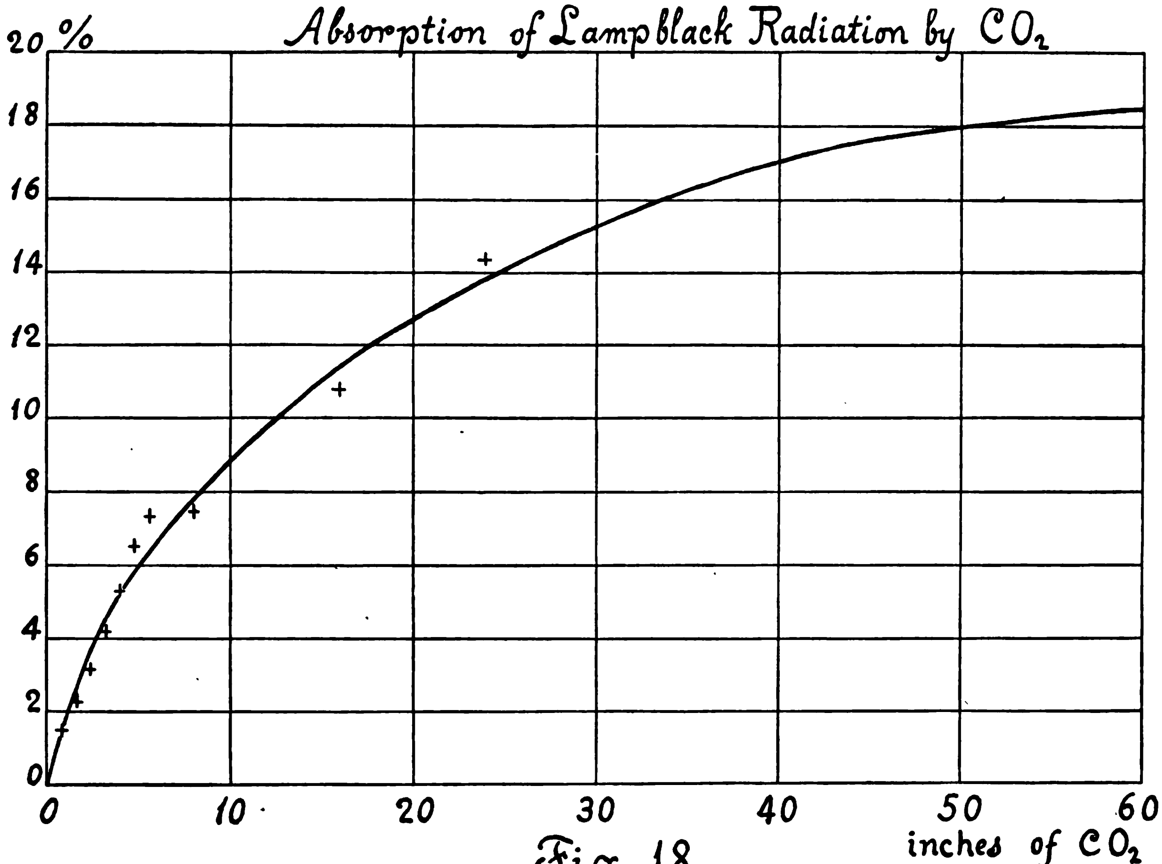

Fig. 18

Temperature-excess.	Radiation of CO_2 through rock-salt, affected by CO_2 absorption but corrected for salt.
50° C.	$\{93 + (169 - 55)\} \times (10)^{-9} \div 0.75 = 207 \times 10^{-9} \div .75 = 276 \times 10^{-9}$
80° C.	$\{260 + (306 - 96)\} \times (10)^{-9} \div 0.75 = 470 \times 10^{-9} \div .75 = 627 \times 10^{-9}$
100° C.	$\{482 + (427 - 128)\} \times (10)^{-9} \div 0.75 = 781 \times 10^{-9} \div .75 = 1041 \times 10^{-9}$

Finally these values must be further corrected for absorption by 4¼ inches of carbon dioxide. Only approximate estimates are available for this quantity. From Tyndall's *Contributions*, page 185, Table XXXV, two minimum values of the absorption may be obtained A layer of CO_2 34 inches deep absorbed $\frac{2.45}{3.7} = 0.662$, and one 13.1 inches deep absorbed $\frac{10.2}{16.8} = 0.607$ of the radiation from a more distant layer of the same gas. A smooth curve through these points and the zero point, as in fig. 19, gives an absorption of 40 per cent. for a depth of 4¼ inches. Since a portion of the radiation came from the walls of a metal tube and was more transmissible than the gaseous radiation, and since the gaseous radiation does not increase much after the third foot, the true absorption of its own rays by CO_2 is certainly greater than that given, but I am unable to fix a more definite value for the absorption by the smallest depth. Accordingly, the true radiations which the bolometer might have recorded, if it could have received the unobstructed emission of rays from a free layer of carbon dioxide 141.8 cm. deep, are:

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* See my determination of this quantity. *Astrophys. Journ.*, vol. 8, p. 211, Nov., 1898.

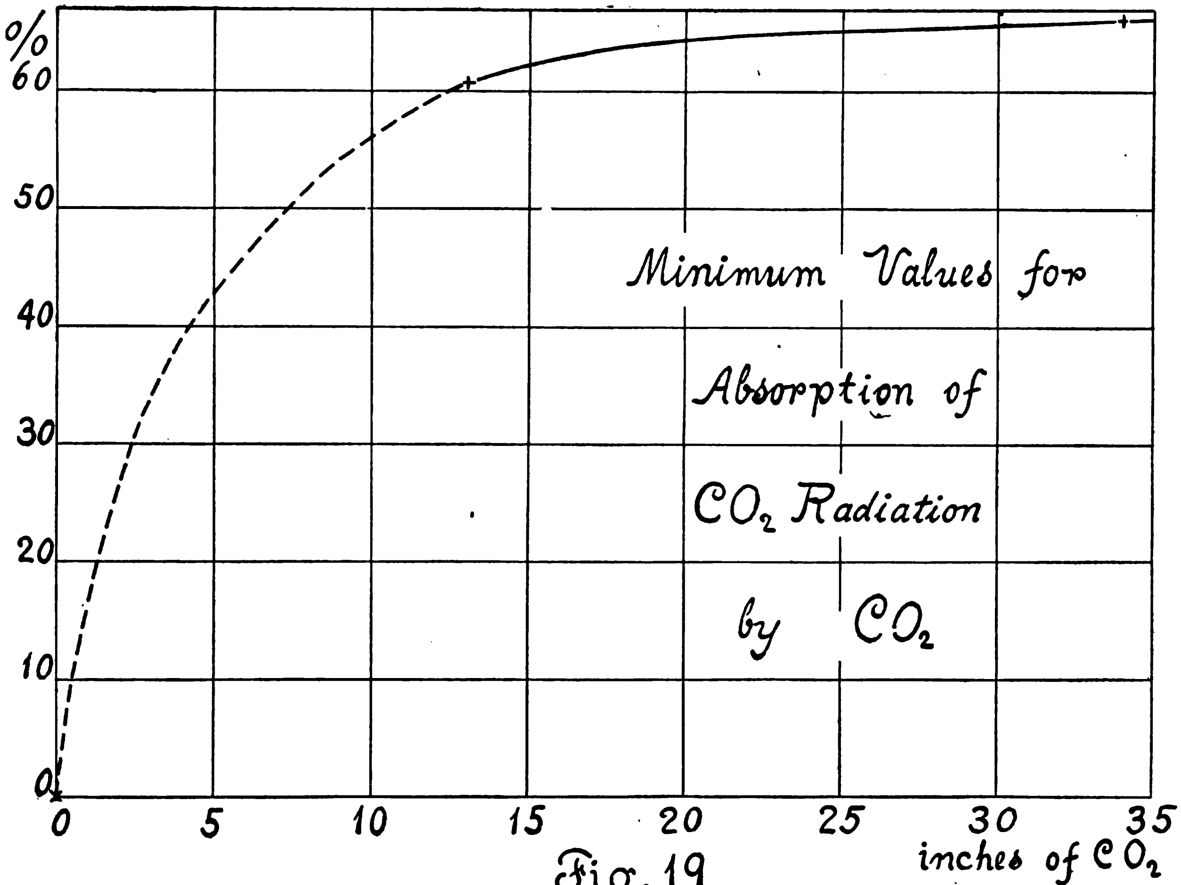

Fig. 19

(50°) $276 \times 10^{-9} \div .6 = 460 \times 10^{-9}$ radim.
(80°) $627 \times 10^{-9} \div .6 = 1045 \times 10^{-9}$ radim.
(100°) $1041 \times 10^{-9} \div .6 = 1735 \times 10^{-9}$ radim.

Absorption by dry air being, according to Tyndall, one-ninetieth that of carbon dioxide, the corresponding disk-corrections for air are, respectively, 1, 2, and 3 $\times 10^{-9}$, and with further allowance for absorption by rock-salt the corrected air radiations are:

(50°) $(139 + 1) \times 10^{-9} \div 0.75 = 187 \times 10^{-9}$ radim.
(80°) $(390 + 2) \times 10^{-9} \div 0.75 = 523 \times 10^{-9}$ radim.
(100°) $(723 + 3) \times 10^{-9} \div 0.75 = 968 \times 10^{-9}$ radim.

The radiation of carbon dioxide is thus found to exceed that of air in every case. The absorption of rock-salt for air radiation may differ from the absorption found for ordinary low-temperature sources of radiation, but not greatly, as the close agreement of results obtained by Method B without absorbent plates proves. (*Ante*, p. 71.)

Tyndall's comparisons of radiations from gases dynamically heated (quoted *ante*, p. 76) were made with 3-foot layers. As I have already explained, the radiation of carbon dioxide is almost exactly the same for a 3-foot layer as for one of 5 feet; but the air radiation with the shorter depth is reduced proportionally. Hence at 50° excess the radiation of 3 feet of air should be

$$\frac{3}{5} \times 188 \times 10^{-9} = 112 \times 10^{-9} \text{ radim},$$

or about one-fourth of the corresponding radiation from carbon dioxide. Thus the discrepancy between my measures and those of Tyndall no longer exists after the application of the final corrections, or, rather, at first sight, is turned to the opposite side.

Theory gives 30.5° C. as the temperature-excess produced by the dynamic heating of air at normal pressure flowing into an exhausted receiver, and 23° C. is the corresponding temperature from the dynamic heating of carbon dioxide. The observations of the radiation of CO_2 with a cooling cylinder, however, do not extend as low as this, and nothing will be gained by substituting results at the theoretical temperature in the preceding computation.

We may now test a conjecture put forth by Tyndall, that a residual deflection remaining after absorption of the radiation of a dynamically heated gas by a cold layer of the same gas is due to radiation from the walls of the tube to which heat has been transferred by contact. "To these latter" [rays], he says, "the gas in the second chamber would be much more permeable than to the former, and to these latter, I believe, the residual deflection of 6°, or thereabouts, is mainly due. That this number turns up so often, although the radiations from the various gases differ so considerably, is in harmony with the supposition just made. In the case of carbonic oxide, for example, the deflection is reduced from 13.7° to 6.3°, while in the case of nitrous oxide it is reduced from 19.5° to 6.2°; in the case of olefiant gas it is reduced from 59° to 10.4°, while in other experiments (not here recorded) the deflection by olefiant gas was reduced from 44° to 6°." (*Contributions*, p. 186.) With the quadruple ratio (4.11 : 1), which I now give for the radiations of carbon dioxide and air, and calling the unknown tube radiation x, the apparent radiations measured by Tyndall from 36.3 inches of CO_2 (deflection = 16.8°), and from air (deflection = 8° to 9°) give

$$x = \frac{(4.11 \times 8.5) - 16.8}{3.11} = 5.8$$

justifying Tyndall's supposition, and incidentally supporting the accuracy of both his and my measures. After wandering through such a maze of corrections as the foregoing an independent check does not come amiss.

The true radiations from the dynamically heated gases in Tyndall's work were

$$CO_2,\ 11.0°;\ \text{air},\ 2.7°;$$

but the large deflections, obtained when blackened tubes were used, were probably due, as I have suggested (*ante*, p. 76–77), to heat developed by condensation of gases in the pores of lampblack.

The experiment on the radiation of steam (*ante*, p. 72) may now be reduced. The density of steam at 135° C. (excess 97°), and at normal pressure, being $\frac{1}{583}$, the liquid equivalent of 142 cm., at 126 mm. pressure, is

$$142 \times \frac{1}{583} \times \frac{126}{760} = 0.040\ 381 \text{ cm.},$$

which by fig. 13 (*ante*, p. 91) will absorb 5.1 per cent. of radiation from lampblack at 100°. The disk having an excess of 97°, the correction for absorption of disk-radiation by vapor and salt may be taken as

$$2942 \times 10^{-9} \times 0.051 \times 0.75 = 113 \times 10^{-9} \text{ radim},$$

and the apparent radiation of steam, reduced with the instrumental constant at the epoch, is

$$38 \times 43.8 \times 10^{-9} = 1664 \times 10^{-9} \text{ radim}.$$

The absorbent layer contained 0.000 224 cm. of equivalent liquid water whose absorption exercised on the special aqueous rays is by no means negligible, as shown by Tyndall's observations on the aqueous absorption of rays from the hydrogen flame (cited *ante*, p. 88), from which an absorption of about 1.9 per cent. may be inferred in the present case, and the measurement of radiation from a 5-foot layer of low-pressure steam, as finally corrected, is:

$$\frac{\{113 + 1664 + (0.019 \times 1664)\} \times 10^{-9}}{0.75} = 2412 \times 10^{-9} \text{ radim.}$$

Reduced to radiant emission to a complete hemisphere, this becomes 0.01247 radim, which is about 81 per cent. of the constant for lampblack at the given temperature.

Before stating the total gaseous radiation a more accurate reduction of the observations at different depths than was possible before shall be given.

From the curve (fig. 18) the values of CO_2 absorption of disk-radiation, corresponding to even feet, are taken and used to correct the percentages in Table 40. By page 108, the correction to CO_2 radiation for absorption of disk-radiation (both being absorbed by rock-salt) is $\frac{299}{482} = 62$ per cent. This will appear in the final column of the next table, the other numbers in this column being derived from it.

TABLE 70.

Depth of CO_2	CO_2 absorption of disk-radiation.	$a-a_1$	$b=\frac{a-a_1}{12.9}$	Correction $c=b\times 62$ per cent.
Inches.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
4½	a_1= 5.5	0	0	0
12	a_2= 9.6	4.1	31.8	+19.7
24	a_3=13.9	8.4	65.1	+40.4
36	a_4=16.4	10.9	84.5	+52.4
48	a_5=17.8	12.3	95.3	+59.1
60	a_6=18.4	12.9	100.0	+62.0

Applying the corrections in the last column to the observed radiations we have:

TABLE 71.

Depth.	0.35 foot.	1 foot.	2 feet.	3 feet.	4 feet.	5 feet.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
CO_2 radiation	0	33.3	72.0	98.7	100.0	97.1
Correction (c)	....	+19.7	+40.4	+52.4	+59.1	+62.0
Sum		53.0	112.4	151.1	159.1	159.1
Corrected CO_2 radiation expressed as a percentage of the highest value.	0	33.3	70.6	95.0	100.0	100.0

The air values in Table 40 will not be changed appreciably by a correction for the absorption of disk-radiation by air. Accordingly, the percentage of radiation from different depths of the two gases may now be finally stated.

TABLE 72.

	CO_2	Air.		CO_2	Air.
Feet.			*Centimeters.*		
5	100	100	125	100	125
4	100	80	100	100	100
3	99	60	75	91.5	75
2	80	40	50	70.5	50
1	48	20	25	40.5	25
			2.5	6	2.5

Values obtained with the factor E_2 (p. 23), and representing the actual radiation falling upon the bolometer as measured in absolute units, are reduced to hemispherical emission by multiplying by the factor:

$$\frac{2\pi \times (28.7)^2}{0.19 \times 5.2685} = 5170$$

An approximate conception of the relations between the total radiation passing through the unit of surface in the unit of time, the temperature, and the depth from which radiation proceeds, may be obtained for carbon dioxide and air by combining the variations from change of temperature with those for change of depth, which is done in the following table (73) completing the experimental part of this research.

TABLE 73.

Depth.	125 cm.		100 cm.		75 cm.		50 cm.		25 cm.		2.5 cm.	
	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.	Air.	CO_2.
°												
100	.00442	.00897	.00353	.00897	.00265	.00821	.00176	.00632	.00088	.00363	.00009	.00054
90	.00325	.00697	.00260	.00697	.00195	.00638	.00130	.00491	.00065	.00282	.00007	.00042
80	.00238	.00540	.00190	.00540	.00143	.00494	.00095	.00381	.00048	.00219	.00005	.00032
70	.00173	.00417	.00138	.00417	.00104	.00382	.00069	.00294	.00035	.00169	.00004	.00025
60	.00123	.00319	.00099	.00319	.00074	.00292	.00049	.00225	.00025	.00129	.00002	.00019
50	.00086	.00238	.00068	.00238	.00051	.00218	.00034	.00168	.00017	.00096	.00002	.00014
40	.00056	.00169	.00045	.00169	.00034	.00155	.00023	.00119	.00011	.00068	.00001	.00010
30	.00035	.00111	.00028	.00111	.00021	.00102	.00014	.00078	.00007	.00045	.00001	.00007
20	.00019	.00064	.00016	.00064	.00012	.00059	.00008	.00045	.00004	.00026	.00000	.00004
10	.00008	.00027	.00006	.00027	.00005	.00025	.00003	.00019	.00002	.00011	.00000	.00002

These values in fractions of a radim are plotted in Fig. 20.

At 100° C. excess of temperature, and at a somewhat greater excess above the freezing point, air 1 cm. deep radiates 0.000 036 radim, or 0.000 000 36 radim per degree. With an excess of only 1° C. the radiation may be estimated as about 0.000 000 06 radim. These quantities are considerably smaller than the 0.000 001 14 radim found by Professor Hutchins (*Am. J. Sci.* (3) vol. 43, p. 362, 1892), who, however, did not dry his air. Moreover, as has been shown, Professor, Hutchins underestimated the depth of the radiant layer of gas, which makes his measurement of radiation per unit of depth too large. On the other hand, my values exceed that deduced by Maurer from meteorological considerations, namely, 0.000 000 011 6 radim. The difference here is very likely due to absorption by air of its own radiation, where large masses are involved, as in the atmosphere.

The region of the spectrum in which the radiation of air lies, may possibly be inferred from the following facts: A region of powerful oxygen absorption exists in the ultraviolet, to which, in all probability, a strong band of emission corresponds; but it is not likely that any emission, produced by simple heating, can be felt in this part of the spectrum at low temperatures. The linear oxygen absorption groups—A, B, and α—in the red, and a series of faint diffuse bands, of which the strongest corresponds with Brewster's telluric band δ ($\lambda = 0.565\mu$ to 0.585μ) in the yellow, together with any others of a like order which await identification in the infra-red, are too insignificant to have emission counterparts which will account for any appreciable fraction of the low-temperature radiation of this gas. Nitrogen and argon are, so far as we now know, of still less importance, since no telluric bands have as yet been traced to their presence in the atmosphere.

Two facts remain to be considered. Hutchins found that a plate of quartz, 0.5 cm. thick, reduced the deflection from hot air from 151 div. to zero; and it has been noted (*ante* p. 34) that 0.315 cm. of glass appeared to transmit 8 per cent. of air-radiation. Besides the region of quartz-absorption at 0.103μ, H. Rubens and E. F. Nichols (*Phys. Rev.*, vol. 5, p. 105, Aug., 1897) have found bands of metallic reflection and total absorption for this substance at 8.50μ, 9.02μ, and 20.75μ. The first two of these bands, with the neighboring region from 8μ to 9.5μ through which transmission by a layer of quartz, so thin as $18u$, does not exceed 10 per cent. (Nichols, *Phys. Rev.*, vol. 4, p. 307, 1897), can not cover the atmospheric bands which we are seeking, since in this part of the spectrum solar rays pass through the atmosphere easily, and the principal emission of radiation from hot aqueous vapor, between 5μ and 8μ, also lies outside of this region. Hence it is perhaps permissible to infer that the low-temperature emission of air, which is so completely absorbed by quartz, has a wave-length not far from 20.75μ, and that air also absorbs strongly in this region; but, if so, the ratio of air-radiation to the radiation of carbon dioxide ought to diminish as the temperature rises, at least until those very high temperatures are attained which favor the emission of the ultra-violet band of oxygen, and there is no evidence of this. I am not disposed to insist upon my observation of a feeble transmission of radiation from air by glass, because it rests upon a very small deflection, but, if genuine, it indicates a discontinuity and essential difference in the absorptions by glass and quartz at this extreme wave-length.

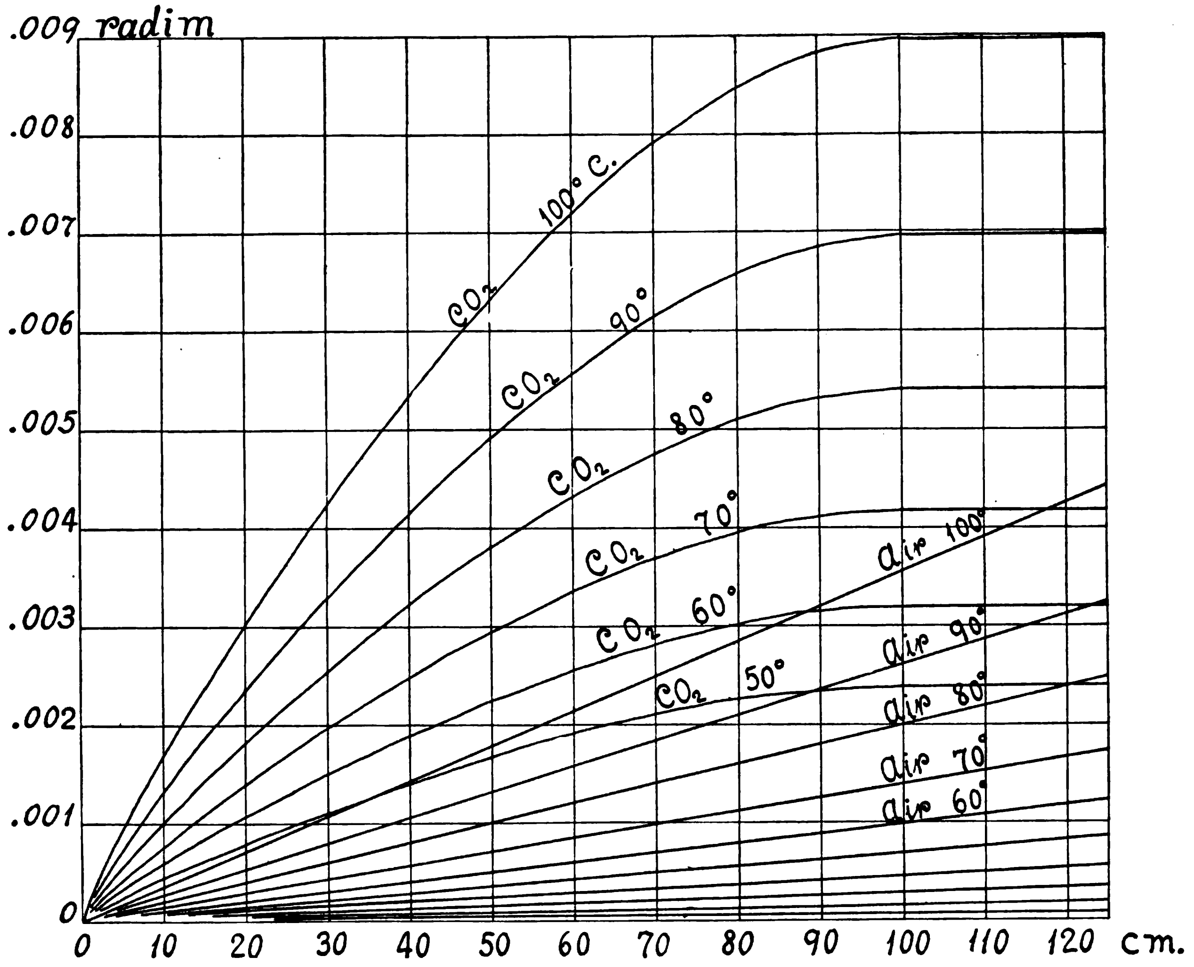

Fig. 20

Variation of Gaseous Radiation With Depth and Temperature.

GENERAL APPLICATION OF THE PRECEDING STUDIES OF ABSORPTION AND RADIATION TO THE PROBLEMS OF ATMOSPHERIC RADIATION.

We have seen that a highly absorbent gas, and one which is also an equally powerful radiant in thin layers, may have little more radiative power than a bad radiator when the depths are greater, the positions of the two being finally reversed at still greater depths, as indicated by the extended curves of fig. 20, and that, in fact, there is not as much difference as might be imagined between the radiation of the different constituents of the atmosphere at ordinary temperatures and when in large masses. The facility with which a highly radiative vapor parts with its heat is largely annulled by self-absorption of its own radiations in deep layers, and since in gases heat is transferred from molecule to molecule with the greatest ease, it is probably a fact that small masses of mixed gases or vapors, such as are used in laboratory experiments, radiate chiefly by their most highly radiative molecules, the others transferring their heat to these kinetically;* but in such great masses as are concerned in atmospheric thermal and radiant processes, it is the feebly radiative molecules which act as radiators, except in a comparatively thin outer layer.

While laboratory experiments are necessary for a correct understanding of the processes which go on in the simplest cases of gaseous radiation and absorption, actual quantitative values which may be of use in large-scale meteorological computations will probably still have to be derived by meteorological methods.

There seems to be some analogy between the radiant powers of dry air and rock-salt. Both, if the suggestion on page 113 be accepted, emit ether-waves of very great length. Both are highly transmissive in that part of the spectrum where fall the emissions from bodies at ordinary temperatures. In small masses they are very bad radiators, but their relative radiant efficiency increases with the depth of the radiant layer.

The powerfully radiant vapors, such as ammonia, like the metals among solids, radiate from a very feeble depth. In the spectral region of their principal emission, after exceeding this depth, no further increase is to be expected, even though the radiant layer be increased to infinity; and as the radiations of these vapors are limited to definite spectral regions, the total emission must finally exhibit an equally definite relation to that of a black body, depending upon the position and extent of those parts of the spectrum within which the vapor is a perfect radiator. In like manner, a gas which is very feebly absorbent or radiant in thin layers, has some depth of maximum efficiency at which its peculiar bands attain the greatest possible development. If these bands, while feeble, are wider, or occupy more extensive regions of the spectrum than those of the strongly radiant vapor, and are of such wave-lengths as to be emitted with equal readiness at the given temperature, the gas in a layer of great depth may surpass a like depth of vapor as a radiator, although, when in thin layers, the vaporous radiation immensely exceeds the gaseous. Again, if the emission bands of the gas are more numerous, and occupy very extensive regions of the spectrum, while those which can be emitted by the vapor at the same temperature are of small extent, a layer of the gas less than the depth of maximum efficiency (except, perhaps, at some temperature which especially favors the vapor's emission) may radiate better than the vapor, the feebleness of the gaseous emission-bands being compensated by their great number or wide range through the spectrum. The rate of increase of radiation with temperature-elevation will depend also upon the region of the spectrum to which the emission is confined, long waves increasing in strength more slowly than short waves. .

The discrepancies between the results of different observers of gaseous radiation, working under various conditions of depth, temperature, etc., after the elimination of errors involved in methods of observation, are capable of being reconciled, and seem to demand varieties of spectral structure, such as those which have been mentioned, for their explanation. To apply the argument to the components of the atmosphere: Carbon dioxide, so far as is now known, has only three emission-bands in the infra-red. Within narrow spectral limits, the radiation of this gas is very powerful, requiring only about a meter-layer to give maximum efficiency. The almost equally slow increase of air-radiation with rise of temperature is perhaps due to the long wave-lengths of its bands; but the very gradual growth of its radiation as the depth enlarges is best explained by the supposition of an extensive spectral region filled with numerous feeble emission-bands which grow in strength very slowly as the depth increases, but which, nevertheless, in their sum total, eventually surpass the radiation of the few strong bands of carbon dioxide. Whether oxygen, nitrogen, or argon are concerned in this primarily feeble emission can not be stated. In a different category from either of the other atmospheric constituents, is water-vapor. Its spectrum consists of many bands composed of very numerous fine lines. Some of these bands are strong, reaching maximum development with a slight depth, while others grow slowly. The extent of spectrum filled with these groups is very great, and thus the radiation is large with a small thickness of vapor, and yet continues to increase through a wide range of depths. The importance of aqueous vapor as a radiator is therefore great; nevertheless, in layers of atmospheric dimensions, there may not be as much difference in the relative efficiency of atmospheric constituents as might at first appear. Throughout the greater part of this vast aerial envelope the gaseous molecules can not radiate, except so far as the stronger radiators emit to the weaker, and these to the outer world. The different sorts are quite independent of each other, but those of a kind are hemmed in by other molecules of the same absorbent properties which cry "no thoroughfare" to ether-waves which have their own vibratory period. Thus it is that, in the upper air, temperature remains almost constant through day and night, and only changes as the vertical circulation of storms, and the general movement of the entire atmosphere from equator to poles and back, replaces the air at any given level and terrestrial position by other air which has acquired its temperature elsewhere under freer conditions. Only at the borders of its domain is any constituent of the air entirely free to change its temperature by its own radiation.

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* See Tyndall's experiments in "varnishing" air molecules with those of more powerfully radiant vapors.

An important relation results from the facts embodied in the theory of a maximum radiant depth in a gas, when combined with the further knowledge that this depth is reached at different distances for particular wave-lengths, and is quickly attained for those rays which lie near the maximum of an emission-band. It seems permissible to say already that so far as gaseous radiation depends upon simple heating of the gas, the ordinates of the maxima in bands of different wave-length (the depth being sufficient to give maximum radiant efficiency for these special rays) are related to each other in the same way as are the ordinates in the spectral energy-curve of a black solid body. As the temperature rises, the heights of the emission-bands of short wave-length increase more rapidly than those corresponding to the longer waves, and with the limitation noted as to manner of excitation, bands at the shortest wave-lengths only become sensible at those high temperatures at which similar radiations first appear in the spectrum of a black solid. Not only is this relative agreement maintained, but the absolute energies in the spectrum at a gaseous band-center and at the same point in the spectrum of lampblack for the same temperature are almost identical, any slight inferiority of the gaseous radiation being probably attributable to the linear constitution of the band and the absence of the condition of maximum efficient depth for some of the rays of the complex bundle. This point has been established for aqueous vapor and carbon dioxide by the observations of Paschen on the emission of heated gases. After noticing facts brought forward by Pringsheim, among others that thin wires are only heated to about 150° C. by certain flames, such as that of carbon bisulphide, "which, notwithstanding, send out an abundant and absolutely blue light," and commenting that, in spite of the low temperature of the wires, "the luminous molecules may, nevertheless, have a very high temperature"—a conclusion which has also been reached by Smithells on theoretical grounds—Paschen demonstrates experimentally that, whatever part chemical action may have in originating high temperatures, the vapor of water and carbon dioxide whose discontinuous emissions make up the chief part of the spectrum from a Bunsen-burner flame, radiate solely by virtue of their heat, however imparted. The emission-bands discovered by Julius in flame-spectra were reproduced by Paschen by simply heating the gases without any combustion whatever. The emission-bands of carbon dioxide were "still certainly perceptible" with the gas at 73° C., at which temperature there can be no question of dissociation or of chemical action; and the emission from aqueous vapor was followed to 280° C. The maximum of CO_2 radiation at wave-length 4.3μ, exhibited the following intensities at the given temperatures: At 842° C., 566 div.; at 707° C., 357 div.; at 450° C., 114 div.; at 306° C., 37 div.; at 204.5° C., 11.1 div.; at 165° C., 6.6 div.; at 114° C., 3.0 div.; and the highest maximum of water-vapor at wave-length 2.7μ gave: At 900° C., 146 div.; at 638° C., 25.4 div.; at 496° C., 5.6 div.; at 400° C., 2.1 div.; at 284° C., 0.6 div. (*Wied. Ann.*, Bd. 50, S. 428, 429, 1893.)

Here radiation has increased with temperature at a more rapid rate for water than for carbon dioxide, or in accordance with the usual law for continuous spectra where the shorter waves have a more rapid rate of increase of energy than the longer; but the relation between the intensities of maxima in different parts of the spectrum is not given by these experiments, since the maxima compared do not belong to the same substance, nor can it be a definite one even for a single radiator unless the depths exceed maximum efficiency for every one of the bands.

In the spectrum of steam, 7 cm. deep, at 500° C., the heights of the long-waved maxima are nearly equal to the corresponding ordinates in the spectral energy-curve of lampblack at the same temperature. At wave-length 5.6μ, "where the water-vapor spectrum has the intensity 87 mm., lampblack at 500°, under like conditions, gives a galvanometer deflection of about 110 mm." At 6.5μ "these intensities are for water 66, for lampblack about 80," but at 2.7μ "on the other hand, for water 139, for lampblack 320 mm.," showing that the depth of 7 cm. is insufficient to fully develop the radiation of the last-named band. (*Wied. Ann.*, Bd. 51, S. 36, 1894.) The height of the emission-maximum at 2.7μ was increased from 20 mm. to 139 mm. when the depth was increased from 3 mm. to 70 mm. (*Loc. cit.*, p. 35.)

The changes in the spectral energy-curve of radiant aqueous vapor produced by variations of temperature are still more marked than those from varying depth. Thus while the aqueous absorption is most intense in the long-waved bands, and while these bands are also most prominent in the emission at low temperatures, the band at 2.7μ has a height twenty times as great as the former in the spectrum of the oxyhydrogen flame. Hence different bands in the spectrum of the same substance follow different laws of increment, both as to temperature and as to depth.

Carbon dioxide at wave-length 4.3μ, in even so small a depth as 7 cm., behaves very much like a black body, both as regards the absolute intensity of its radiation and its variation with the temperature. Paschen's curve for the latter quantity (*Wied. Ann.*, Bd. 51, Taf. 1, fig. 9) falls but little below the corresponding curve for lampblack, indicating that 7 cm. is very near the maximum efficient depth for certain rays from this gas.

It is not to be expected that a vapor which is quite colorless and transparent for luminous rays should give a continuous visible spectrum even when highly heated; but the same gas in another part of the spectrum may have its vibrations damped through a wide range of wave-length, provided the depth or density of the radiant layer be sufficient. The wide bands thus produced resemble those limited spectral regions within which certain phosphorescent solids and liquids radiate exclusively, but without giving definite line-spectra.

Strongly colored gases which absorb visible rays emit continuously in the same visible region of the spectrum. Mr. J. Evershed's experiments on the radiation of heated gases (*Phil. Mag.* (5), vol. 39, p. 465, 1895) prove "that besides iodine, the vapors of bromine, chlorine, sulphur, selenium, and arsenic can all be made more or less incandescent by heating to the temperature at which glass combustion-tube softens, and the light emitted by each of these glowing vapors appears to givé a perfectly continuous spectrum, while the corresponding absorption-spectra are selective. Thus there is no such close relation between emission and absorption as is implied by Kirchoff's law of radiating bodies. There seems, however, to be a general relation between the total absorbing and radiating power for the visible rays."

The production of those distinct and widely separated vibrations which give line-spectra, demands considerable freedom of motion, such as exists in the partial vacuum of a Geissler's tube, in the high dilution of minute traces of metallic salts distributed through the mass of a Bunsen flame, or in the very thin surface layers at the inner and outer surfaces of such a flame, where chemical action is going on. Spectral differences are also found at different flame-levels, testifying to a succession of chemical interchanges which undoubtedly favor the production of line-spectra. Thus, cupric chloride in the Bunsen flame gives successive sheaths of yellow, red, blue, and green flame, due to metallic copper, cuprous chloride, and cuprous oxide, as Professor Smithells has shown by means of his cone-separator for studying the flame of the Bunsen burner. (*Phil. Mag.* (5), vol. 39, p. 122, 1895.) Very brilliant spectra of the copper salts may be obtained by means of a copper wire which has stood for some time in hydrochloric acid, and has become deeply corroded. There is also in this case a partial separation of the flame-effects as successive layers of the corroded film burn off.

The mechanism by which the discontinuous radiations of the electric glow in rarefied gases and of flames are produced has been the subject of much speculation. Werner Siemens, in 1882, wrote:

> If we assume that the gas-molecules are surrounded by a sheath of ether, an alteration of these sheaths of ether must take place when two or more such molecules combine chemically. The resultant movement of the ether-particles must be compensated by vibrations which may form the starting point of the outflow of waves of light

and radiant heat. In quite a similar way we can picture the light-effects which appear when an electric current is passed through gases. (*Wied. Ann.* Bd. 18, S. 315.)

Since the current conducted by gas appears to be always accompanied by chemical action, the glow might be explained as in flames through the oscillating environment of the etherial sheaths of the gaseous molecules by which the passage of the electricity will be facilitated. (*Loc. cit.*, p. 316.)

Others have imagined the gaseous molecule to consist of a congeries of atoms whose configuration being changed by electrification, or during the act of chemical combination, for example, certain of the atoms being temporarily separated from their groups, or ionized, there results a series of atomic oscillations about a mean position, until the energy of the disturbance is dissipated as radiant energy of similar periods. As thus stated, this hypothesis offers no suggestion of the mode by which energy is transferred from the atoms to the ether. But if the gaseous molecule is composed of linked atomic vortices of ether, or of associated concentric vortices, in which are critical or limiting surfaces, conditioned by changes of form or velocity of etherial movement, the rearrangement of these groups determined by chemical interchange, or their disturbance from positions of equilibrium by electrification, may engender waves in the critical surfaces whose periods depend upon the dimensions and surface-velocities of these loci. The passage of systems of waves over such closed surfaces may give foci of interference, and it is possible that the connection and order observed in the frequencies of the numerous sorts of vibrations which the atoms of one element can execute simultaneously, or at least in such rapid recurrent succession that the series can not be distinguished from a simultaneous one, are to be thus interpreted.

The hypothesis of Arrhenius which assumes ionization of a gas wherever line-spectra are produced, demands a certain amount of ionic dissociation even at comparatively low temperatures, and this has perhaps not been demonstrated except under peculiar conditions of electrification; but whether, for example, we conclude as Liveing and Dewar did (*Proc. Roy. Soc. London*, vol. 30, p. 152, 1880; see also vol. 34, p. 418, 1882, where somewhat conflicting testimony is given), that the bands in the spectrum of the blue base of a Bunsen flame are due to carbon and hydrogen in the act of uniting or separating, in the formation or destruction of acetylene, the chemical union of these two substances being considered essential to the exhibition of this spectrum, or whether, with Lockyer and others, the spectrum in question be attributed to carbon vapor alone, I think we must agree with Arrhenius that it is an atomic rather than a molecular motion which produces the line-spectrum, and, in general, it is molecular motion which gives extensive diffuse bands, such as those of the absorption-spectra of liquids, and the absorption and emission spectra of some gases.

Is it necessary, however, that atoms should be completely free in order that their vibrations may give line-spectra? A distinction between the spectra of free and of partially constrained atoms may be granted, but it seems permissible to assume that some of the most persistent vibrations may be emitted by atoms in the midst of their aggregations which constitute the molecules. Prof. A. A. Michelson ("On the broadening of spectral lines," *Astroph. Journ.*, vol. 2, p. 251, Nov., 1895) finds that rarefied hydrogen (pressure about 1 mm.) gives out its characteristic spectrum under the action of an electric discharge at a remarkably low temperature. The width of a line having been proved to increase as the temperature rises in the ratio of the square roots of the absolute temperatures, the width of the red hydrogen line in an unheated tube was found to correspond to a temperature not more than 50° C. above the surroundings, or 320° absolute. The emission of *visible* radiations at such a low temperature implies that the rays are not produced by simple heating (molecular motion or rectilinear motion of free ions), but that the passage of the electric spark by ionic motions increases the motions (either rotations or oscillations) within the molecules, modifying the internal atomic motions without changing the rectilinear velocities of the atomic aggregates to any great extent. On the contrary, since hydrogen and other simple gases may be heated to very high temperatures without causing them to emit visible radiations, it is evident that the shocks produced by external collisions, due to rectilinear motions, are not as efficacious in setting up internal atomic vibrations as are the torsions experienced during the passage of a spark. The aurora is a case in point. In the middle latitudes it occurs usually at heights exceeding 40 miles, where the air is intensely cold, and is an instance of visible atmospheric radiation produced, not by direct thermal means, but electrically.

The experiments with dust-laden air have indicated that the addition of a small amount of solid matter, diffused through a large volume of air, does not change the radiating power of the latter perceptibly. The same conclusion may be drawn from the use of smoke to prevent frost, for if the finely divided carbon increased the radiating power of the air, the protection would be less effectual. The principal result which can be traced to the presence of floating dust is its modification of atmospheric transmission by the reflection and scattering of rays during their passage through the turbid medium.

Tyndall imitated the blue color of the sky, and even the peculiar polarization of its light—which is a maximum 90° from the sun, and which exhibits neutral points where the plane of polarization changes—by precipitating a mist of attenuated solid or liquid particles, of scarcely more than molecular dimensions, from mixed rarefied vapors capable of reacting chemically under the influence of light. By choosing substances, "*one* at least of whose products of decomposition under light shall have a boiling point so high that as soon as the substance is formed it shall be *precipitated*," solid or liquid particles of great fineness are produced without having time to cohere into coarser agglomerates. "By graduating the quantity of the vapor this precipitation may be rendered of any degree of fineness, forming particles distinguishable by the naked eye, or particles which are far beyond the reach of our highest microscopic powers." (*Contributions to Molecular Physics*, p. 431, from *Proc. Roy. Soc. London*, No. 108, 1869.)

As the particles become coarser they cease to reflect selectively, at least in the visible spectrum, but return light of every refrangibility in nearly equal proportion. In this way a cirro-stratus cloud spreads white light all over the sky, overpowering the blue light. In like manner a fog, dense enough to obscure the rays of the sun, may diffuse enough of sunlight to produce quite a bright general illumination; but in this case the reflection is not absolutely devoid of selective properties. To the palm of the hand held up, the position of the unseen sun is revealed through the sensation of warmth produced by solar rays of great wave-length which are capable of penetrating the mist. The obscure rays may also be recorded by the actinometer, and analyzed by the spectrobolometer, which shows that a mist, capable of keeping out all of the visible rays in the direct beam, may still transmit infra-red waves beyond $2\,\mu$ rather freely.

Lord Rayleigh (*Phil. Mag.* (5), vol. 47, p. 375, 1899) finds that diffraction from the molecules of the air, which are of small dimensions relatively to the waves of light, is competent to account for a large part of the selective scattering of short waves in sky-light, and for the actual transmission of the visible part of the spectrum. If x is the distance through which light must pass in air at atmospheric pressure before its intensity is reduced in the ratio of the basis of natural logarithms to unity,

$$x = \frac{3\,n\,\lambda^4}{32\,\pi^3\,(\mu - 1)^2}$$

where n is the number of molecules in the unit of volume, or $19 \times (10)^{18}$ per cubic centimeter according to Maxwell, μ is the refractive index as modified by the spherical molecules, $\mu - 1 = .0003$, and λ is the wave-length of light. Taking Bouguer's estimate of the transmission of star-light by an entire atmosphere, namely 0.8, we find, since the maximum sensitiveness of the eye for light as faint as that of the stars is about at wave-length

$$\lambda = 5 \times (10)^{-5} \text{ cm.},$$
$$x = 40 \text{ kilometers.}$$

The homogeneous atmosphere being 8.3 kilometers thick, the observed transmission by 40 kilometers is:

$$(0.8)^{\frac{40.0}{8.3}} = 0.34$$

which does not differ much from the assumed transmission, $\frac{1}{e} = 0.37$.

If Bouguer's eye was most sensitive to yellow rays at $\lambda = 6 \times (10)^{-5}$ cm., $x = 83$ kilometers, and the corresponding observed transmission, $(0.8)^{10} = 0.11$, is less than a third of that computed by the hypothesis of molecular diffraction, leaving a considerable part of the blue light of the sky to be supplied from other sources. There can be no doubt, however, that the exponent of λ should be larger than 4 at the blue end of the spectrum, and smaller than 4 in the infra-red, as Lord Rayleigh suggests (*loc. cit.*, p. 383). The formula, as it stands, gives for $\lambda = 0.293\mu$ a transmission by one atmosphere of 0.17, and for $\lambda = 1.0\mu$ a transmission of 0.99; but the former is known to be zero, and the latter, as far as it depends on selective scattering, is probably more nearly equal to $0.99 - 0.17 = 0.82$. The sudden termination of the solar spectrum at 0.293μ may be produced by a local absorption-band of oxygen, but selective scattering gives nearly the same limit.

Cornu (*Comptes rendus*, t. 88 and 89) finds that the limit of atmospheric transmission in the ultra-violet with a clear sky, depends on the barometric pressure, thus on the oxygen and nitrogen contents, rather than on aqueous vapor or other variable constituent of the air. If it were not for this fact it might be supposed that the molecules of water-vapor, or the products of condensation resulting from the continual diffusion of a very rare aqueous vapor into the upper atmosphere, might be the sole cause of sky-color, since, as Tyndall remarks (*Heat as a Mode of Motion*, p. 414), "the color of the firmamental blue, and of distant hills, deepens with the amount of aqueous vapor in the air," and in part this may be an additional cause of coloration, although it appears to be of no importance in determining the limit of the spectrum. The association of the deepest blue sky with the descending air of the tropical calms may be explained by the purification which the air has undergone. The coarser dust having been washed out in the abundant precipitation of the equatorial rains, the genuine color of the sky resulting from molecular diffraction is no longer obscured by the more general scattering of light by the larger and unassorted particles.

The beautifully colored coronas and patches of color seen upon incipient cirrus near the sun are due to diffraction from ice or water particles of a coarser order than the molecular, and graduate into cases of simple and indiscriminate reflection from still coarser particles, an effect which becomes very great at large angles of incidence, and produces the strong glow around the sun, never absent except in a sky of exceptional purity, such as can only be found at great altitudes.

Whymper in his *Travels Amongst the Great Andes of the Equator*, page 324, thus describes the effect of clouds of volcanic dust from Cotopaxi:

> When they commenced to intervene between the sun and ourselves the effects which were produced were truly amazing. We saw *a green sun*, and smears of color something like verdigris green high up in the sky, which changed to equally extreme blood-reds, or to coarse brick-reds, and then passed in an instant to the color of tarnished copper, or shining brass. No words can convey the faintest idea of the impressive appearance of these strange colors in the sky—seen one moment and gone the next—resembling nothing to which they can properly be compared, and surpassing in vivid intensity the wildest effects of the most gorgeous sunsets.

I think there can be no doubt that these vivid colors were entirely due to diffraction, owing their brilliancy to the uniformity in the size of the particles producing them. The description reminds one of the colors of soap bubbles in sunshine. Cirrus clouds are apt to be composed of ice crystals in the act of forming from vapor. The particles are constantly growing in an irregular way, and numerous diffraction rings produced by means of swarms of particles of as many different diameters, are superimposed, so that the blended colors are not pure, and there is much white light.

In general, a part of the diminution of solar rays in passing through the air is due to selective scattering by air-molecules, to which diffraction by ice-crystals of minute size, and reflection from dust of every sort may be added in a hazy atmosphere; but these causes have very little influence upon the true atmospheric radiation which consists chiefly of long waves but little affected by dust.

SUMMARY.

The exposition of a few leading principles is needed to give entrance and guidance in a general survey of the subject. Atmospheric radiation is so extensively modified by atmospheric absorption of rays that the subject of the atmosphere's transmissive power must be included.

The atmosphere by its molecular constitution produces a selective scattering of the rays which pass through it, which is greatest for the short waves. Ether-waves of greater length than 2μ are but little affected by selective scattering, but throughout the visible spectrum there is an increasing depletion of the direct radiant beam, progressing a little more rapidly than the inverse fourth power of the wave-length. The rays taken out of the direct beam in this way do not alter the temperature of the air, and a large part of them reach the Earth's surface. The same is the case with the light diffracted by minute ice-crystals, or more indiscriminately reflected by coarser dust-particles.

An entirely different process is involved in the production of local line and band absorption. Special rays are absorbed by the atoms and molecules of the various atmospheric constituents. Here the energy which exists in the ether as radiation is transformed into the energy of molecular or atomic movement, and remains in the atmosphere as an increase either of its sensible temperature or of its latent heat. The ultra-violet rays appear also to produce chemical change in some of the atmospheric substances, accompanied by electrification. The composition of the atmosphere is being continually changed by emanations from the Earth and its inhabitants, and the atmospheric thermal energy is increased in this way, and especially by the latent heat of vaporization of water. Heat is also developed dynamically whenever there are descending movements in the air. High winds in dry and dust-laden air generate large amounts of frictional electricity, and a part of this thermal and electrical energy imparted to the air from many sources, is eventually given out again in the form of radiation.

The actual spectral energy-curve of a depleted sunbeam is a complex of an exceedingly variegated original radiant energy, as further modified by telluric absorption, every one of whose lines and bands has a separate origin and law of variation. In like manner the radiation emitted by the air is made up of a great variety of individual lines and bands, each having a law of its own, depending on the pressure, depth, temperature, and physical state of the productive constituent. In a measure the emission by the air resembles its absorption, but is confined to the longer waves when thermally produced at relatively low temperatures. Unknown regions in which the oxygen, nitrogen, argon, and krypton of the atmosphere radiate at low temperatures, remain to be explored. The chief radiations which can now be definitely placed in the spectrum are those of aqueous vapor and carbon dioxide. Owing to the feebleness of these radiant bands at low temperatures, the positions and relative intensities of the more refrangible ones are best studied in the absorption-curve of the solar spectrum.

The following table (75) of positions and intensities of infra-red bands in the solar spectrum has been compiled from two plates—(*a*) *A* to ω_2, (*b*) ω_1 to deviation 38° 45′—accompanying an article on the "Infra-red solar spectrum of a 60° rock-salt prism," published in the *Annual Report of the Smithsonian Institution* for 1897, Appendix V, pp. 66–68. The standard temperature of the prism is stated to be 20° C. "The positions of about 225 absorption lines and bands are determined * * * between deviations of 40° 25′ and 38° 45′, corresponding to wave-lengths 0.76 μ and 5.20 μ, respectively." These curves are the culmination of Langley's long labors in the solar spectrum. No band is included in the present list which is not also shown on the three bolographs exhibited by Professor Langley at the Oxford meeting of the British Association (*Astrophysical Journal*, vol. 1, p. 162, pl. 9, Feb., 1895). The numbers assigned here to the intensity of absorption at the centers of the individual bands have been obtained by comparing the bolographic ordinates with those of a smooth curve passed by estimation through the unabsorbed maxima. A list of these maxima and their intensities in the prismatic spectrum follows:

TABLE 74.

Minimum deviation.		Intensity of radiation.	
°	′		
40	24.5	11	[14]
40	9.0	24	[28]
39	56.4	38	[45]
39	47.0	54	[64]
39	38.0	63	[77]
39	28.5	31	[62]
39	12.0	18	[36]

The numbers in brackets are the values obtained by correcting for atmospheric absorption. The adopted curve has been made symmetrical on the side of greater wave-length to allow for the undoubtedly very large absorption of the entire spectrum as the great bands of water-vapor and carbon dioxide are approached, since in this region the intervening points of comparatively unabsorbed energy begin to be encroached upon by the bands. The corrected values have been assigned after taking account of the extensive stretch of almost total absorption between 5 μ and 8 μ, and the probable form of the original spectral energy-curve before the radiation entered the Earth's atmosphere has been inferred by supplying these missing regions. The limits adopted for the breadths of the bands and groups of bands are somewhat arbitrary, owing to the very gradual way in which the slopes of the energy-curve begin:

TABLE 75.

Designation of band.	Minimum rock-salt deviation.	Wave-length.	Transmission.	Absorption.	Wave-lengths assigned by other observers.	Source and remarks.
	° ′	μ	*Per cent.*	*Per cent.*		
Great A	40 24.0	0.76	1÷14.2= 7.0	93	Abney.	Telluric.
A_1	40 23.6	0.77	2÷14.5=13.8	86	Photography. Diffraction grating.	Oxygen.
Brewster's Y_1	40 16.7 to 15.5	0.82	10÷20.6=48.5	52	.816-.821	Includes solar Na .818.
" Y	40 15.3	0.825	8÷21.3=37.6	62	.823	
" X_3	40 15.0 to 13.5	0.83	9÷22.4=40.2	50	.825-.832	
" X_1	40 12.2	0.855	16÷24.6=65.0	35	.854	Solar Ca.
" X	40 11.7	0.86	15÷25.2=59.5	40	.866	
Abney's π	40 10.5	0.875	20÷26.4=75.8	24		Telluric, probably aqueous.
	40 7.7 to 6.6	.895- .91	18÷30.0=60.0	40	.895-.903	
	40 6.6 to 6.0	.91 - .915	18÷30.9=58.3	42	.905-.911	
	40 6.0 to 5.2	.915- .92	18÷31.8=56.6	43	.912-.918	
Rho-tau group	40 4.6 to 39 59.5	0.925 to 0.985				Breadth, 0.060μ.
Abney's ρ	40 4.6 to 3.5	.925- .935	6÷33.4=18.0	82	.930-.939	Telluric, probably aqueous.
" σ	40 3.5 to 1.3	.935- .965	8÷35.7=22.4	78	.943-.950	
" τ	40 1.3 to 39 59.5	.965- .985	23÷38.4=59 9	40		
	39 58.7	1.00	32÷41.4=77.3	23		
	39 54.8	1.06	37÷48.3=76.6	23		
Great phi group	39 53.7 to 39 47.0	1.085 to 1.24				Breadth, 0.155μ.
Abney's Φ	39 53.7 to 51.6	1.085 to 1.125	9÷52.7=17.1	83		Telluric water vapor.
	39 51.6 to 51.1	1.125-1.13	11÷55.0=20.0	80		
	39 51.1 to 49.8	1.13 -1.16	13÷56.9=22.8	77		Includes solar Na 1.132.
	39 49.3	1.17	39÷59.4=65.7	34		
	39 48.5	1.19	43÷60.9=70.6	29	Grating and spectrobolometer.	
υ	39 46.5 to 45.2	1.25 -1.28	45÷66.0=68.2	32	Paschen.	
Great psi group	39 45.0 to 39 38.2	1.28 to 1.52			Bunsen flame, 1.33μ to 1.50μ.	Breadth, 0.240μ.
	39 43.7	1.32	29÷70.9=40.9	59		Telluric water vapor.
Abney's Ψ	39 43.0 to 41.0	1.34 -1.40	4÷73.4= 5.4	95		
	39 40.8	1.405	8÷75.0=10.7	89		
	39 39.9	1.44	16÷76.1=21.0	79		
	39 37.5	1.54	58÷76.8=75.5	25		
	39 36.8	1.57	58÷76.4=75.9	24		
	39 36.1	1.59	58÷75.9=76.4	24		
Great omega group	39 34.8 to 39 28.5	1.65 to 2.03			Bunsen flame, 1.75μ to 2.10μ.	Breadth, 0.370μ.
Langley's Ω	39 33.0 to 30.8	1.75 -1.87	1÷66.4= 1.5	99		Telluric water vapor.
" ω_1	39 30.3 to 29.6	1.91 -1.97	9÷65.0=13.8	86		
" ω_2	39 29.6 to 28.5	1.97 -2.03	21÷63.0=33.3	67		

TABLE 75—Continued.

Designation of band.	Minimum rock-salt deviation.	Wave-length.	Transmission.	Absorption.	Wave-lengths assigned by other observers.	Source and remarks.
	° ′	μ	*Per cent.*	*Per cent.*		
Great chi group	39 28.0 to 39 11.5	2.08 to 3.48			Bunsen flame, 2.42μ to 3.02μ.	Breadth, 1.400μ. H_2O+CO_2.
Langley's X	39 23.7 to 17.9	2.36 -2.86	1÷49.0=2.0	98		
" χ_1	39 17.2	2.92	3÷43.5=6.9	93		Telluric water vapor.
	39 16.4	2.99	3÷42.5=7.1	93		
	39 15.9	3.02	9÷41.7=21.6	78		
" χ_2	39 15.0	3.10	3÷40.3=7.4	93		
	39 14.3	3.15	5÷39.3=12.7	87		
	39 13.8	3.20	4÷38.6=10.4	90		
	39 13.2	3.24	7÷37.8=18.5	82		
	39 12.6	3.29	12÷36.8=32.6	67		
	39 11.3 to 10.7	3.41 -3.46	14÷34.5=40.6	59		
	39 10.7 to 9.6	3.46 -3.53	14÷33.3=42.0	58		
	39 9.1	3.58	11÷31.8=34.6	65		
	39 7.0 to 6.3	3.73 -3.80	9÷29.0=31.0	69		
	39 6.3 to 5.5	3.80 -3.87	9÷28.2=31.9	68		
Great upsilon group Υ	39 5.5 to 38 55.0	3.87 to 4.60			Grating and spectrobolometer, Paschen. Bunsen flame, 4.15μ-4.39μ.	Breadth, 0.730μ, telluric carbon dioxide.
	39 2.0 to 38 56.5	4.12 to 4.43	1÷21.4=4.7	95		

The great bands of which the radiation of the atmosphere at slight excess of temperature mainly consists, lie in the infra-red spectrum beyond the limit of this table. Fig. 21 is a provisional spectral energy-curve of the radiation of moist air for the temperature + 50°C. The positions of the bands rest upon the observations of Paschen, Rubens, and Aschkinass, and relate to the emission from aqueous vapor and carbon dioxide, with the exception of the radiant energy of extreme wave-length, which I have provisionally assigned to one or more of the permanent gases, nitrogen, oxygen, etc., on the strength of Hutchins' observation of the absorption of air radiation by quartz.[*]

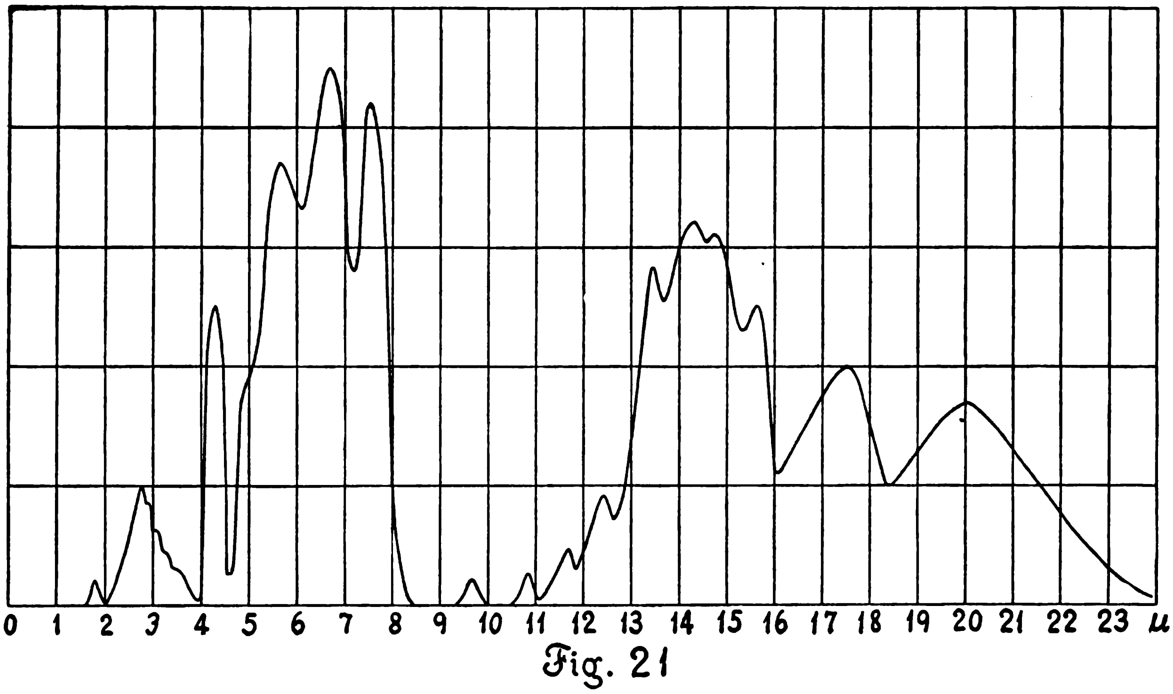

Fig. 21

Approximate spectral energy-curve of air radiation.

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[*] See p. 112.

The form of the curve will vary according to the temperature and composition of the air. The relative heights of the maxima are assumed to vary inversely as the absorption, but some deviation from this rule must be anticipated. Similar curves for depths of air giving maximum radiant efficiency at the principal bands may be constructed for other temperatures by first drawing the appropriate energy-curve for a black body, and then inserting and graduating the heights of the radiation-bands, so that the highest may be included by the curve.

It has been explained that a considerable part of the radiation of short wave-length diffused by the dust and finer particles of the atmosphere, reaches the surface of the earth.* Not so, however, that portion of solar radiant energy which has suffered the special absorption which causes the cold bands of the infra-red spectrum. This energy remains in the air as an increase of temperature, and is subsequently lost again as atmospheric radiation; but since the greater density and humidity of the surface air obstructs downward radiation, and since, further, in any radiant interchange which can proceed through the deeper and denser layers the excess of expenditure is in the hotter air, which is usually beneath, it follows that atmospheric radiation, with rare exceptions, proceeds mainly outward.

Suppose that one-fifth of the entering radiation remains behind in a layer of air 20 kilometers deep. Then during one hour in the middle of the day, the solar constant being 0.05 radim, $\frac{1}{5} \times 0.05 \times 3600 = 36$ small calories will be imparted by the sun to each column of 1 sq. cm. section and 2,000,000 cm. high. The upper layers have the opportunity of attacking an unsifted sunbeam and of taking out those rays at the band-centers which are totally absorbed by very small quantities of matter. Hence in spite of the rarefaction of the air and of its chief absorbent at high altitudes, the absorption per unit of absorbent material being very much greater at the start, the actual distribution of absorption at different altitudes may be tolerably uniform. If the heat developed in the extinction of solar rays is distributed uniformly through the entire 20 kilometers, each kilometer receives 1.8 small calories in a vertical column of 1 sq. cm. section during one hour in the middle of the day, and the consequent elevation of temperature is 0.7° C. at an altitude of 20,000 meters, but only 0.07° C. at a height of 1,000 meters. The upper part of the first layer, because it receives the undepleted rays, will continue to absorb with the same intensity during the hours of sunshine, and the entire layer on account of the obliquity of the rays and longer paths with a low sun will absorb more powerfully as the sun's altitude diminishes, and at the equinoxes might have its temperature raised at least 8.4° in one-half day if none of the heat were lost; but as the losses certainly exceed the gains, the diurnal range is not likely to be more than one-half of this amount.

The deeper layers of air receive solar radiation which has been depleted of its more absorbable rays, and as the sun nears the horizon a relatively larger part of the energy remains in the upper air, whence the lowest layers may not be heated in one-half day more than four or five times as much as in one hour at midday, and the diurnal range of temperature due to absorption of solar rays probably does not exceed two or three tenths of a degree in the 2 or 3 kilometers of air above the surface. Very much larger ranges occur in the first 1,000 meters from the ground, but they are due to ascent of air heated by contact with the soil and cease at an altitude of about 1,000 meters, where the lower cumulus clouds mark the upper limit of this convection. (See "Exploration of the air by means of kites" at the Blue Hill Meteorological Observatory, *Ann. Harvard Coll. Astron. Obs.*, vol. 42, part 1, p. 103, 1897.) Only in case the previous sifting had deprived the sunbeam of all of its absorbable rays, or provided the thermal energy were lost by reradiation as fast as it is received, could there be a complete absence of thermal effect.

The advancing part of an anticyclone receives air directly depleted of moisture in the preceding area of precipitation. The dry air is a bad radiator, and the full increment of temperature by compression in the descending air is preserved. Hence the adiabatic rate of cooling in unsaturated air with increase of altitude is maintained or exceeded in the front part of the anticyclone, as Clayton has observed (*loc. cit.*, p. 118). But in the western part of the anticyclone and the advancing region of a following cyclone the greater easterly velocity of the upper air carries along an overhanging mass of warm, moist air which diminishes or reverses the upward fall of temperature. The alternation of hot and cold waves in winter brings a considerable range of temperature in the lower air which must not be confounded with that produced by the direct absorption of solar radiation.

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* See the previous chapter on atmospheric dust, p. 118.

The depth of 20 kilometers has been taken as defining somewhat approximately the part of the atmosphere within which water-vapor can exist in appreciable quantities or what may be called the aqueous atmosphere.

It is evident, after what has been said in regard to the small depth from which atmospheric radiation can pass freely, that radiant emission from so great a depth of air as 20 kilometers, or even from a small fraction of a kilometer, can only take place by the slow process of one portion of air radiating to a neighboring one which is at a slightly lower temperature, and this in turn to other volumes not far away, the process being repeated over and over again until the upper regions of freer transmission are reached.

The curve of transmission of radiation by the terrestrial atmosphere, given in fig. 22, is intended to represent only the most important features. It relates to a vertical transmission through a clear air of only moderate humidity, and includes (1) the general fact of selective scattering of short waves, (2) the progressive strengthening of band absorption in the infra-red, due mainly to water-vapor, including bands at 0.95μ, 1.1μ, 1.4μ, 1.9μ, 2.5μ, and 4.7μ, until (3) the great bands of this substance between 5μ and 8μ, marked Ξ in the figure (strongest absorption at 5.9μ, 6.5μ, and 7.5μ), are reached, (4) the greater but decreasing transmission beyond 9μ with absorption-bands at 9.6μ, 10.9μ, 11.6μ, 12.4μ, 13.4μ, 14.3μ, 15.7μ, 17.5μ, and perhaps at 20μ, still attributable to aqueous vapor, with the exception (5) of a wide band extending from 12.5μ to 16μ with a maximum of absorption at 14.7μ, denoted by △ in the figure, which with the band at 4.3μ and the smaller one at 2.7μ, is produced by carbon dioxide, and finally (6) a region of almost total absorption beyond 20μ, here provisionally attributed to the permanent gases of the atmosphere.

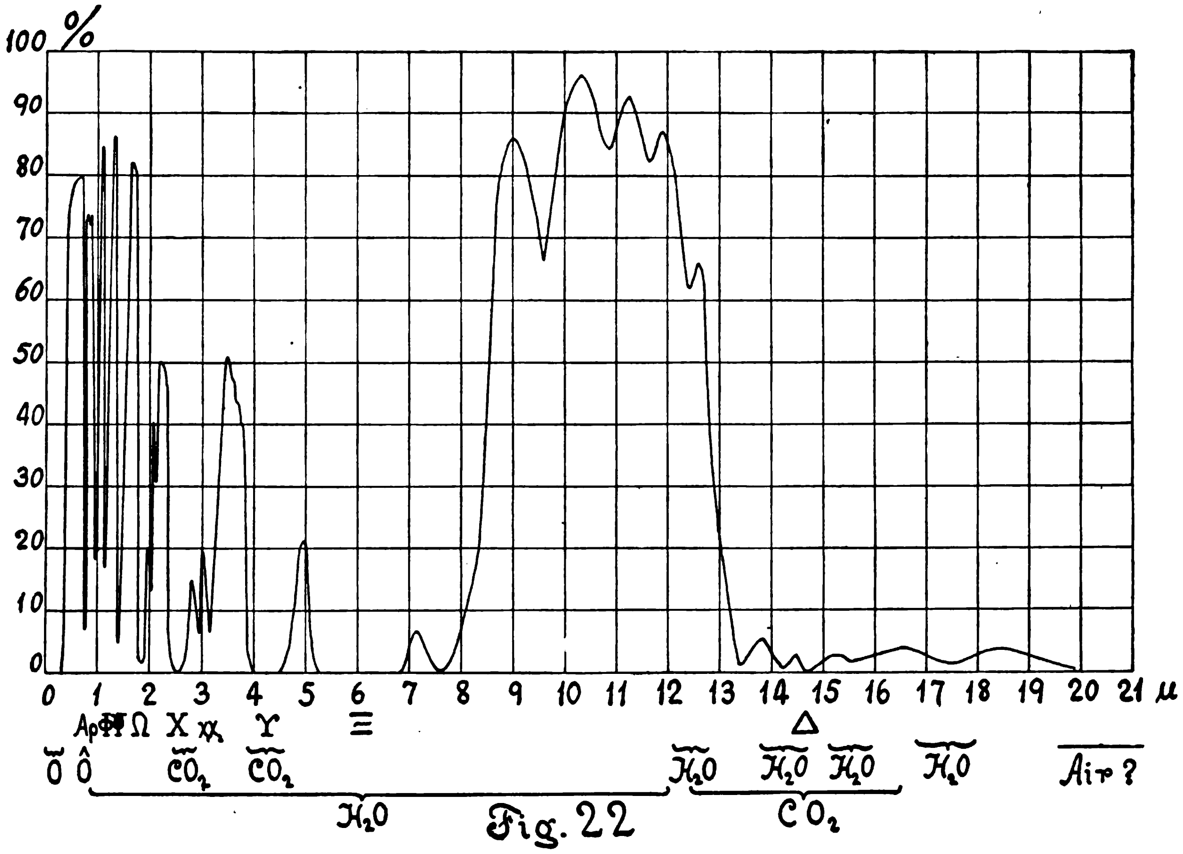

Fig. 22

Transmission of radiation by the Earth's atmosphere.

The absorption by carbon dioxide, by water-vapor, and possibly also by the permanent gases, practically obliterates the solar spectrum beyond 13μ, since the unabsorbed radiation is here very feeble.

Some of the consequences of atmospheric absorption may be briefly pointed out. The absorbent action of carbon dioxide and the permanent gases is almost invariable; but the absorption bands of aqueous vapor are much stronger in summer than in winter, and the selective scattering of short waves also increases in summer. One result of this variation is that the direct rays of the midday sun, received upon a normal surface, are more powerful in winter than in summer, in spite of the greater distance traversed by the sunbeam through the air in winter. Dr. Emil Bessels* noted that the rays of the arctic sun in early spring, although making a very small angle with the horizon and penetrating a great depth of air, affected the actinometer much more intensely than later in the season after the sun had risen higher, but when the air had become moist.†

The direct effect of the sun's rays upon a normal surface is less in the tropics than in temperate regions, and less at sea level than upon a mountain top, owing to the difference in the aqueous component of the air; and the ability of the solar radiation to maintain a high temperature in the torrid zone or at sea level is due to the accumulation of the thermal energy imparted to the Earth's surface by reason of the retention of the escaping radiation from that surface by a moist and highly absorbent atmosphere rather than to the direct power of the sunbeam. The position of the great water band (Ξ in fig. 22) covers a region of the infra-red spectrum in which terrestrial radiation is near its maximum, and the emission from the soil is still strong at the great $\varDelta$ band; but the sun's rays are most powerful in the visible spectrum where aqueous absorption is small and the bands of carbon dioxide completely lacking. Thus the penetrative power of the incoming is greater than that of the outgoing rays, and this relative difference, which increases with the amount of moisture in the air, produces an accumulation of thermal energy at the Earth's surface, which would generate a very high temperature were it not that the sign of the function is reversed after sundown. The cumulative effect of continuous sunshine gives a mild summer to the arctic regions with a sun of lower altitude than that which brings vigorous winter weather in lower latitudes, continuity of accumulation more than compensating the advantage of greater transmission in winter.

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* *Scientific Results of the U. S. Arctic Expedition. Steamer Polaris.* Vol. I, Washington, 1876. § Solar Radiation, pp. 80–82.

† In Lieutenant Ray's *Report of the International Polar Expedition to Point Barrow, Alaska* (Washington, 1885), differences of black and bright bulb thermometers are given for this station between February 1 and August 27, 1883. During the month of March differences above 45° F. were measured on twelve days, during April on fourteen days, during the first half of May on seven days; but after this the differences did not again reach 45°. In June a difference greater than 40° was only attained on three days, and during July and August the excess of the black bulb did not once reach 40°. This sequence of low readings is no doubt partly due to the greater cloudiness of the summer months, for the black-bulb thermometer requires time to reach a maximum reading which often fails to be recorded during the brief intervals between clouds. Nevertheless, the highest reading of all, 82°.3 F., being made on the 8th of May, which has its parallel in the frequent maximum reading at 9 or 10 a. m. in a diurnal curve of intensity, confirms the result of Dr. Bessels, and with many other similar facts, proves that altitude of the sun above the horizon is not the only important factor conducing to intense solar radiation.

The reader may also consult the *Report on the Proceedings of the U. S. Expedition to Lady Franklin Bay*, by Adolphus W. Greely, vol. 2, p. 377, Chart No. 17 (Washington, 1888). The curve of solar radiation attains its maximum in May, and it is noted that "the effect of increasing humidity or aqueous vapor in intercepting the solar [radiant] heat is shown in a most marked manner."

These observations of solar radiation were made with conjugate bright and black bulb thermometers in vacuum chambers of glass, an instrument which, as we now have it, is not capable of giving accurate quantitative values. The chamber is supposed to be a vacuum, but there is usually no means of verifying the supposition. Minute quantities of certain vapors, condensible at low temperatures but evaporated in hot sunshine, may alter the indications widely. If it is desired to get rid of all convection and penetration of gaseous molecules within the envelope, a very perfect vacuum must be obtained, and variations either in the degree of exhaustion or in the material of the transmitting walls will produce serious discrepancies in instruments exposed side by side. Glass also does not transmit the longer radiations readily, and the amount rejected will vary with the thickness and quality of the glass, with the nature of the surrounding surfaces, and especially with the previous depletion in passing through the atmosphere, which is the very thing we are seeking. A part of the heat registered comes from short-waved sky reflection, and this is relatively greater with a low sun; nevertheless the existence of an absolute low-sun maximum radiation can not be thus explained, and since the chief defect of the instrument is that it shuts out much of the radiation of long wave-length and obscures its variation, it is quite possible that a perfect actinometer would show as great or greater seasonal fluctuations.

The heat entrapped through the differential transmission of solar and terrestial radiation by aqueous vapor and carbon dioxide is mainly stored in the lower layers of the atmosphere, and because the absorption by air heavily loaded with moisture is nearly complete for its own radiation, this stored-up energy continues for a long time as a controlling balance wheel in the mechanism of the weather. As long as the mantle of water vapor remains unbroken, thermal fluctuations are kept within narrow limits. Storms may make inroads upon the continuity of this aqueous atmospheric envelope, but evaporation of moisture restores the rents. Rolled up in great bosses covering hundreds of thousands of square miles of territory, the thickened mantle of vapor brings hot waves. Displaced by downward movements bringing the dry air of the upper atmosphere to the surface, corresponding cold waves result. The gradual accumulation of moisture in higher and higher atmospheric layers during the summer, clothes the temperate regions with so deep a protective covering of moist air, that summer conditions are prolonged in the autumn to a time which is astronomically the correlative of late winter. The absence of this deep protective layer, whose formation can only be effected gradually, permits late frosts in spring, long after the sun has resumed his ascendency. In the middle of a sunshiny day, by the evaporation of moisture from the earth's surface and its ascent in convection currents, the vapor of water is carried up to high levels; but during the night most of this accession of moisture is diffused into colder or drier regions of the upper air, where it is either condensed and no longer exists in the air as vapor, or is so diluted and reduced in relative humidity as to be of slight absorptive value when the sun next rises. The increase of moisture in the upper air at midday is the cause of the flat-topped diurnal actinometric curves which are observed on all but the coldest and driest days. As the sun mounts above the horizon, the intensity of his rays augments, giving an actinometric curve, which, on an exceptionally dry day, is approximately a parabola, symmetrical about the midday ordinate; but, in general, the apex of the curve is truncated, and after about 9 a. m. the curve becomes flat-topped with minor fluctuations indicating the activity of the convective process, and the passage of invisible clouds of vapor across the line of sight. At the same time the curve of relative humidity of the surface air becomes deeply depressed, while at high levels the tension of aqueous vapor increases in the middle of the day, indicating the rapid removal of aqueous vapor from the lower to the upper air. The earth has its lowest temperature and the air, if clear, its greatest transmission in the early morning hours when, as a whole, the atmosphere, according to observations at high levels, has its smallest content of aqueous vapor, a condition which is evidently correlated with the maximum actinometric effect observed by Bessels in the arctic spring months.

It appears certain that on our Earth surface temperatures lower than — 73° C., or 200° absolute, can not occur, possibly because of the almost total absorption by the atmosphere of all radiations beyond 13μ. Paschen's law of the wave-length of the maximum in the normal spectral energy-curve of a black body gives at this temperature:

$$\lambda\ max. = \frac{2891}{200} = 14.46\mu.$$

Thus the position of the normal maximum in the energy-curve for the lowest arctic temperature very nearly coincides with the great absorption-band of carbon dioxide (Δ, fig. 22), discovered by Rubens and Aschkinass; and at lower temperatures the maximum would be found at still greater wave-lengths on which the permanent gases of the atmosphere may possibly exercise a complete absorption. In the midst of much conflicting testimony as to the region of the spectrum in which the absorption of pure air resides, this suggestion is at least worthy of consideration.

By the same law a sunlit surface of rock at 340° absolute temperature, if radiating like a black body, must have its spectral maximum at 8.5μ; and taking the mean temperature of the earth as + 15° C., its spectral maximum would reside on the average at 10μ. Some deviation from the law is to be expected and does occur in the spectra of solids, which do not conform to the ideal of blackness. Since it appears to be a general law that the radiation of a body is especially large in that spectral region where its absorption is exercised, it is possible that the radiation of the ocean at a mean surface temperature of + 15° C. will be found to have the maximum in its spectral energy-curve displaced to a wave-length shorter than 10μ, and approaching the great band (Ξ) where the absorption of atmospheric moisture is greatest, and that this is another cause, in addition to the large specific heat and mobility of water, conducing to the slowness of oceanic temperature changes; but more important as a retainer of oceanic heat is the extension of the band Ξ to greater wave-lengths in the absorption of the layer of air nearly saturated with moisture, which always hangs over the water.

The absorption of terrestrial radiation by atmospheric moisture lies somewhere between such curves as those of figs. 14 and 15. Aqueous absorption is very greatly increased as the air approaches saturation, because the molecules of water-vapor then become complex and have an absorptive power approaching that of liquid water.* The absorption of the atmosphere and the surface temperature which can be maintained by its aid, increase both with the absolute and with the relative humidity.

Not only is the absolute temperature of the soil dependent upon atmospheric moisture, acting in conjunction with the heat supplied by the sun's rays, but also the diurnal range of surface temperature. "Where the land is moist the changes of temperature are less than where it is dry or arid," but it is the condition of the air and not that of the soil which makes the radiation possible or impossible. The following illustration under nearly the same insolation must suffice as an example.

After several weeks of rain in May, the daily range for the first week of pleasant weather in June was 9°. 5 C. At the beginning of August, after two months of drought, the range had increased to 12°. 1 C., and the highest range of the week in June (10°. 4 C.) was less than the lowest (10°. 6 C.) of the week in the time of greatest drought.

TABLE 76.

Date.	Range.	Sky.	Date.	Range.	Sky.
	° C.			° C.	
June 3	8.8	Clear—Cirrus.	July 31	11.0	Clear, smoky—Cirrus p. m.
" 4	10.4	Alto-cumulus—showers.	Aug. 1	11.9	" " cloudy evening.
" 5	9.2	Cloudy—Rain.	" 2	11.2	Cloudy, 0.01 inch of rain.
" 6	8.8	Cloudy a. m.; clear p. m.	" 3	12.8	Cumuli.
" 7	10.4	Cirrus—Cumuli p. m.	" 4	14.5	Clear, then cumuli.
" 8	9.5	Clear—Hazy.	" 5	10.6	Clear.
" 9	9.1	" "	" 6	12.4	Clear—Smoky.
Mean.	9.5		Mean.	12.1	

On Pike's Peak the range is greater in winter than on the plains, but less in summer. Here also the mountain climate is relatively drier than that of the plains in winter than in summer.

In free air the diurnal range is small, but in this case because the radiation which has escaped the previous action of the chief absorbent of radiation, water-vapor, is deficient in absorbable rays, and small toll is taken by the air. On a mountain, and still more on a plateau, the increased power of the sun's rays heats the rocks, and thence the surface air, more than at lower altitudes, and unless the wind is so strong as to remove the surface air before it is much heated, replenishing it with cool air from the free atmosphere around the mountain top, the range may be greater on the mountain than on a low-lying plain, because of the more powerful insolation.

The spectrum of the radiation of the atmosphere consists entirely of lines and bands; and since the atmospheric absorption acts within the same limited regions of the spectrum, atmospheric radiation is largely annulled by an absorption which is identical in quality, or as to the kinds of rays affected, with the thing on which it is exerted, and can differ only in regard to the rapidity with which extinction or emission vary with the depth, or by a redistribution of energy, according to which the radiation in process of transmission may be absorbed by one constituent of the atmosphere but emitted again by a different one, or passed on by a series of alternate radiations and absorptions. In any case the depth from which atmospheric radiation can directly proceed is limited, and the amount of the emission is relatively greater for a small depth. Hence laboratory experiments which deal with small layers of air, give radiant values which are too large to be applied without discrimination in meteorological problems.

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* See p. 100, *et seq.*

Owing to the feebleness of the radiation-bands in the spectrum from air at such moderate temperatures as prevail in the atmosphere, and owing further to the limitation of the emission to the outer layers of large masses of air, small effect is to be anticipated from the radiation of elevated bodies of warm air to a cooler underlying surface. Clayton's kite experiments on Blue Hill have demonstrated the existence of high warm layers of clear air above cold layers and a cold surface, when the surface winds are from a cold quarter, and when the surface temperature has been changed very little by the substitution of warm for cold air at the upper level. Radiation effects are immediate, and it is possible that under these circumstances a slight elevation of temperature from the radiation of the warm air may be discriminated in advance of the slower rise of temperature produced by the commingling of air currents and the bodily transfer of superficial air from warmer regions by cyclonic movement. The most advantageous occasion for testing such a possibility is immediately after a severe cold wave in winter, for then the absorbent power of the lower air for the hypothetical radiation from the warm upper layer will be least. The return of an elevated body of relatively warm air after a severe cold wave is usually heralded by an increase of cirro-stratus cloud, and this alone may make surface temperature greater by the action of the aqueous vapor whose presence is made known by the cloud, the vapor imprisoning more of the sun's rays in the daytime, and impeding the escape of terrestrial radiation at night.

I will give two examples of recovery from cold waves, observed at Providence, R. I., taking the data from the records of the City Engineer's Office and of the Ladd Observatory.

Cold wave of January 6 to 10, 1896.—The minimum of — 8° F. on the morning of the 6th was followed by a gradual recovery, lasting four days. Each day saw a recovery of about 7°. The air on the 6th was very dry (relative humidity 22 per cent.). The barometer, which had risen to 30.37 inches on the evening of the 6th, fell very slowly to 29.81 inches on the morning of the 10th. In this case there was no pronounced cyclone, but 3 inches of snow fell from 2 p. m. on the 7th to 2 a. m. on the 8th, and 11 inches from 3 p. m. on the 9th to 7 p. m on the 10th. The clouds began to gather on the morning of the 7th. The wind continued north during the four days, except for a short time on the 9th.

Cold wave of February 16 to 19, 1896.—There was a fall of 2.5 inches of snow, ceasing at 3 p.m. on the 16th. The thermometer, which at 0 a. m. on the 16th was 42° F., fell steadily to —8° F. on the morning of the 17th. The highest temperature on the 17th was + 7° F. at 5 p. m. after a day of unclouded sunshine. The barometer, after 7 a. m on the 17th, was steady at 30.30 inches. Relative humidity rose slowly during the night of the 17th to 18th from 40 per cent. to 55 per cent.; lowest temperature, 0° F. at midnight. Sky clear until the morning of the 18th, when there was a trace of snow (clouds 0.9); temperature + 2°.5 at 6 a.m., February 18th, and barometer falling (30.20 inches). Relative humidity and temperature then increased rapidly, until at 11 p. m. snow began to fall, continuing until 9 p. m. on the 19th, when the barometer had descended to 29.27 inches. The wind continued north until noon of the 19th, when it changed to the southeast. Here a part of the rise of 10°.5 in the first twenty-four hours after the minimum must be attributed to the influence of sunshine. More rapid recoveries than this are almost invariably accompanied by a change of wind to the south, or by a sudden accession of moisture, implying the importation of warm air from a milder neighborhood.

The solar radiation of 0.05 radim often produces a rise of temperature of 15° C. between sunrise and midday (no account being taken of atmospheric absorption). A rise of temperature at the rate of 1°.5 C. in six hours after a cold wave may frequently be observed, indicating a radiation of 0.005 radim, if due to a warm upper layer of air, assuming that the lower layers are dry enough to permit the passage of this radiation with no more obstruction than that which affects the sun's rays. An upper layer of warm and moist air, 10° C. above surface temperature and 1 meter thick, will radiate 0.0002 radim, but the radiation must be twenty-five times as great if the recovery of heat after a cold wave is to be attributed to direct atmospheric emission. Some effect could no doubt be produced by an indirect process involving layers of considerable depth, but there is no warrant for the supposition that the warm upper currents in the cases cited have an excess of 10° *above surface temperature.* The existence of warmer air a few meters above the soil which is unduly chilled by nocturnal radiation at the calm center of an anticyclone is not in question here, for this air, although it is so near, being dry, does not radiate enough to prevent the surface refrigeration.

It seems probable that after the descent of dry air at the center of an anticyclone has ceased and unimpeded surface radiation to space has produced the minimum surface temperature of a cold wave, the gradual recovery of heat and moisture by the lower atmosphere is effected principally by the absorption of the sun's rays, by evaporation from the surface, and by the mingling of air from warmer regions, and that any contribution which atmospheric radiation from upper warm layers may give to this recovery of heat is not likely to produce a rise of temperature of more than 1° C. per day.

The power of warm air to radiate must depend largely on its isolation. An upper body of warm moist air, if freely suspended in the midst of dry air, immediately becomes a good radiator, not only by virtue of its high temperature, but because of its containing an especially emissive substance. The radiation, however, owing to the peculiar absorption of its own rays by the moist air, can only proceed through a small surface layer, which soon becomes saturated by the cooling. The great increase of absorption which has been shown to occur at the condensation point of water prevents further cooling by radiation, except in an excessively thin surface shell of cloud, and it is doubtful if any large proportion of rainfall is produced through cooling of moist air by radiation, even in those towering cumulo-nimbi which ascend into dry regions where the radiant effect is greater. While cumulus clouds may be thimble-shaped shells, the typical rain-cloud generates its rain, not by any skin-squeezing process, but by expansive cooling which affects the entire volume of air.

Air radiation must usually proceed more easily upward than downward, because the higher layers are apt to be drier and more transmissive than the lower. Cooling by radiation, although of small moment in the lower air, must be added to cooling by expansion as a cause for the cold of the high atmosphere; and the diminution of absorption of its own radiation by air at great altitudes on account of lessening aqueous vapor, so far compensates for decrease of radiant power at very low temperatures that cooling by air radiation may be effective to the outer limit of the atmosphere, and may prevent the retention of such molecular velocities as would permit the escape of air molecules, except in the very unusual case of the ejection of intensely hot vapor to great heights by volcanic eruptions. The former prevalence of vigorous vulcanism on the Moon has perhaps had more to do with the loss of the Moon's atmosphere than the smallness of its attraction, at least the fact that one or more of Jupiter's satellites exhibit phenomena which are presumably atmospheric, warns us not to place too great faith in the theory that a small planet must necessarily have a relatively small atmosphere. Another cause which has peculiarly favored the loss of the Moon's atmosphere by the escape of individual molecules of high velocity has been the slowness of its axial rotation, which permits an accumulation of heat during the long day until surface temperatures considerably above that of boiling water are attained. (See the author's "Probable range of temperature on the Moon," *Astroph. Journ.*, vol. 8, Nos. 4 and 5, Nov. and Dec., 1898).

The results of the present research prove that within moderate depths of only a few meters the radiation of dry air, purified from carbon dioxide, increases quite uniformly with the depth; that the radiation of a 1-meter layer of purified air at 50° C. and near atmospheric pressure (735 mm.), as compared with one at 0° C., is 0.00068 radim, representing a transformation and transfer of thermal energy of 0.00068 small calories every second through each square centimeter of limiting surface; that the radiation of a like depth of carbon dioxide at the same temperature is three and one-half times that of air, or 0.00238 radim, which is very nearly a maximum for this temperature, further increase of the radiant depth being unattended by a corresponding addition of radiant energy, showing that equilibrium between radiation and emission has been almost reached at this depth; that the radiation from a layer of steam 5 feet deep at one-sixth of atmospheric pressure is two and one-half times that from a like body of dry air at temperatures near the boiling point of water, and eight-tenths of the radiant emission from the black solid body; while for smaller depths the radiant power of water-vapor is relatively greater, a steam jet of small dimensions radiating over four times as strongly as one of air, a ratio which would doubtless have been considerably greater if the air had been perfectly dry.

There appears to be no reason to doubt that the radiation of a moderate depth of homogeneous air at a given temperature depends on the product of the depth by the density, and remains the same when depth and density vary inversely; but the absorption of a given mass of aqueous vapor has been found to be smaller when distributed through a large volume of air than when concentrated.* The phenomena are conditioned by molecular relations. Reciprocal variation of depth and density does not change the number of molecules which are engaged in the radiant transaction in a homogeneous medium; but dilution by another substance involves a partition of energy among molecules whose radiant and absorbent properties are dissimilar.

As an absorbent of terrestrial radiation aqueous vapor is very much more efficient than any other atmospheric ingredient; but as radiators when in large masses, the substances which compose the atmosphere do not differ as widely as might be supposed, and the position of chief radiant may be assumed in turn by either aqueous vapor, carbon dioxide, or the permanent gases, according as the depths and temperatures of the emissive and absorbent layers change.† The depth of gas which gives maximum radiation at short range is an insignificant quantity compared with atmospheric dimensions, and radiation from either the atmosphere of the Earth or the solar chromosphere is a superficial phenomenon, even when the masses of heated gas measure thousands of miles in thickness. The fineness of the chromospheric lines in the solar spectrum, although the shifts of the Fraunhofer lines indicate pressures of many atmospheres at the base of the chromosphere, is a sufficient demonstration that only the outer layers radiate. If the emission proceeded also from the depths of the chromospheric mass, the lines of hydrogen and some other elements would be greatly widened; and if the Earth's atmosphere radiated unimpeded throughout its depth, its thermal changes and its radiant effects would be enormous. Instead of this, we find the atmosphere playing the part of a conservator of thermal energy, and must gratefully admire the beneficent arrangement which permits the Earth to be clothed with verdure and abundant life.

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[*] See p. 94.

[†] This statement can not be absolutely verified, because the dimensions of my apparatus were insufficient to give the maximum radiation for pure air, but it is strongly indicated by the curves and on theoretical grounds.

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U. S. DEPARTMENT OF AGRICULTURE,

WEATHER BUREAU.

BULLETIN H.

WEST INDIAN HURRICANES.

BY

E. B. GARRIOTT,

PROFESSOR OF METEOROLOGY.

Prepared under direction of WILLIS L. MOORE, Chief U. S. Weather Bureau.

WASHINGTON:
WEATHER BUREAU.
1900.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture, Weather Bureau,
Washington, D. C., April 12, 1900.

Hon. James Wilson,
Secretary of Agriculture, Washington, D. C.

Sir: I have the honor to transmit herewith a paper on the subject of West Indian hurricanes, prepared by E. B. Garriott, Professor of Meteorology, and to recommend its publication as a bulletin of the Weather Bureau.

This paper reviews the writings of the more prominent meteorologists of the nineteenth century, so far as they refer to the tropical storms of the North Atlantic, and presents a chronological list of West Indian storms for four hundred years. It graphically illustrates and describes the more important hurricanes that have occurred during the last twenty-five years, and contains accounts, based upon local records and observations, of historical storms of the West Indies. It presents in a concise form information, obtained from many sources, which is necessary to a practical understanding and appreciation of the character of the storms which visit the territory over which the work of the Weather Bureau has been recently extended.

Very respectfully,

Willis L. Moore,
Chief U. S. Weather Bureau.

Approved.
James Wilson,
Secretary.

WEST INDIAN HURRICANES.

Conceived in the mind of Benjamin Franklin in 1747, the law of storms was in an incubative state for more than fifty years. Referred to by Colonel Capper in 1801, and formally introduced to the world by William C. Redfield in 1821, this law evolved a system of meteorology which at the close of the nineteenth century is a recognized but undeveloped member of the scientific family.

The part taken by Franklin in this creation was the discovery that the northeast storms of the Atlantic coast of North America came, with shifting winds, from the southwest. The position was somewhat similar to that assumed by him in the electrical field, wherein he proved that atmospheric electricity and lightning were identical. Colonel Capper, of the East India Company's service, asserted that hurricanes were whirlwinds whose diameter could not be more than 150 miles, and that these whirlwinds sometimes had a progressive motion. William C. Redfield, of New York, independently announced the discovery, based upon detailed observations taken along the Atlantic coast of the United States, that the whole of the revolving mass of atmosphere which composed the whirlwinds, or hurricanes, of the West Indies advanced with a progressive motion from southwest to northeast, and drew the conclusion that the direction of the wind at any particular place forms no part of the essential character of the storm, and is in all cases compounded of both the rotary and progressive velocities of the storm in the mean ratio of these velocities. He found that while the average diameter of West Indian hurricanes was 150 to 250 miles, their active influence extended over a tract 500 to 600 miles in width; that the duration at any point of the most violent portion of the storms was seven to twelve hours; that they rotated from right to left, and that their average rate of progress from the time they appeared over the eastern islands of the West Indies until they disappeared beyond Nova Scotia was 15 to 20 miles an hour. He remarked that their axis of revolution, or "gyral axis," probably inclined in the direction of their progress, and he ascribed the retardation of the lower part of the revolving mass to the greater resistance at the surface of the earth, in consequence of which the more elevated parts inclined forward and overrun to a very considerable extent the more quiet lower atmosphere. He ascribed the fall in the barometer at places toward which the hurricanes approach to the centrifugal tendency of the immense revolving mass of air which constitutes a storm. He stated that this centrifugal action must expand and spread out the stratum of atmosphere subject to its influence, and toward the vortex or center of rotation must flatten and depress the stratum so as to diminish the weight of the superincumbent column, which presses on the mercury of the barometer. He also conceived that, whatever the upward limit of the revolving mass, the effect of its depression must be to lower the cold stratum of the upper atmosphere, particularly toward the more central portions of the storm, and, by thus bringing it in contact with the humid stratum of the surface, to produce a permanent and continuous stratum of clouds, with abundant precipitation of rain. He speculated on the cause of the hurricanes which visit the Atlantic coast, and conceived that—

> They originate in detached and gyrating portions of the northern margin of the trade winds, occasioned by the oblique obstruction which is opposed by the islands to the direct progress of this part of the trades, or to the falling off of the northerly or eddy wind from the American coast upon the trades, or to both these causes combined.

Additional investigations by Redfield regarding hurricanes were summarized in the United States Naval Magazine as follows:

1. The severest hurricanes originate in tropical latitudes to the north or east of the West Indian Islands.

2. They cover simultaneously an extent of surface from 100 to 500 miles in diameter, acting with diminished violence toward the exterior and increased energy toward the interior of the space.

3. South of the parallel of 30° these storms pursue toward the west a track inclined gradually to the north till it approaches 30°, when their course changes abruptly to the north and eastward, their track continuing to incline gradually to the east, toward which they advance with an accelerated velocity.

4. The duration of a storm depends on its extent and velocity, and storms of smaller extent advance with greater rapidity than larger ones.

5. The direction and strength of the wind in a hurricane (for the most part) are found *not to be in the direction of its progress.*

6. In their *westward* course the direction of the wind at the commencement is from a *northern* quarter and during the latter part of the gale from a *southern* quarter of the horizon.

7. In their *northward* and *eastward* course the hurricane begins with the wind from an *eastern* or *southern* quarter and terminates with the wind from a *western* quarter.

8. North of 30°, and on portions of the track farthest from the American coast, the hurricane begins with a *southerly* wind, which, as the storm comes over, *veers gradually* to the westward, where it terminates.

9. Along *the central portion* of the track in the same latitude the wind commences from a point near to *southeast*, but after a certain period *changes suddenly* to a point almost directly opposite to that from which it had been blowing, from which opposite quarter it blows with equal violence till the storm has passed. Under this central portion the greatest fall of the barometer takes place, the mercury rising a short time previous to the change of wind.

10. On the portion of the track nearest the American coast, or farthest inland, if the storm reaches the land, the wind begins from a *more eastern* or *northeastern* point, and afterwards veers more or less gradually by *north* to a *northwest* or *westerly* quarter, where it terminates.

11. From these facts it follows that the great body of the storm whirls in a horizontal circuit round a vertical or somewhat inclined axis of rotation, which is carried onward with the storm, and that the direction of this rotation is from *right to left.*

12. The barometer in all latitudes sinks under the first half of the storm in every part of its track except, perhaps, its northern margin, and *thus affords the earliest and surest* indication of the approaching tempest. The barometer again rises during the passage of the last portion of the gale.

In the vortex or axis of the revolving storm violent *flaws* or *gusts* of wind alternate with *lulls* and remissions of its violence; and here Mr. Redfield conceived *that the vortex or rotating axis of a violent gale or hurricane oscillates in its course with considerable rapidity in a moving circuit of moderate extent near the center of the hurricane;* and he conjectured that such an eccentric movement of the vortex may be essential to the continued activity or force of the hurricane.

In his third paper Mr. Redfield delineated on a chart the route of several storms and hurricanes, and made the following remarks regarding the results of his investigations:

> It will hardly escape notice that the track of most hurricanes appears to form part of an elliptical or parabolic circuit, and this will be more obvious if we make correction in each case for the slight distortion of the apparent course in the higher latitudes which is produced by the plane projection. We are also struck with the fact that the vertex of the curve is uniformly found near the thirtieth degree of latitude. In connection with this fact it may also be noted that the latitude of 30° marks the external limit of the trade winds on both sides of the equator; and perhaps it may not prove irrelevant to notice even further that by the parallel of 30° the surface area as well as the atmosphere of each hemisphere is equally divided, the area between this latitude and the equator being about equal to that of the entire surface between the same latitude and the pole.

Finally Mr. Redfield deduced the following rules for the guidance of mariners which, even in the light of our present knowledge of the law of storms, are not subject to sweeping modifications:

1. A vessel bound to the eastward between the latitudes of 32° and 45° in the western part of the Atlantic on being overtaken by a gale which commences blowing from any point to the eastward of southeast or east-southeast may avoid some portion of its violence by putting her head to the northward, and when the gale has veered sufficiently in the same direction may safely resume her course. But by standing to the southward, under like circumstances, she will probably fall into the heart of the storm.

2. In the same region vessels on taking a gale from southeast, or points near thereto, will probably soon find themselves in the heart of the storm, and after its first fury is spent may expect its recurrence from the opposite quarter. The most promising mode of mitigating its violence and at the same time shortening its duration is to stand to the southward upon the wind as long as may be necessary or possible, and if the movement succeeds, the wind will

gradually head you off in the same direction. If it becomes necessary to heave to, put your head to the southward, and if the wind does not veer, be prepared for a blast from the northwest.

3. In the same latitudes a vessel scudding in a gale with the wind at east or northeast shortens its duration. On the contrary, a vessel scudding before a southwesterly or westerly gale will thereby increase its duration.

4. A vessel which is pursuing her course to the westward or southwestward in this part of the Atlantic meets the storms in their course, and thereby shortens the periods of their occurrence, and will encounter more gales in an equal number of days than if stationary or sailing in a different direction.

5. On the other hand, vessels while sailing to the eastward or northeastward, or in the course of the storms, will lengthen the period between their occurrence, and consequently experience them less frequently than vessels sailing on a different course. The difference of exposure which results from these opposite courses on the American coast may in most cases be estimated as nearly two to one.

6. The hazard from casualties and, of consequence, the value of insurance is enhanced or diminished by the direction of the passage, as shown under the last two heads.

7. As the ordinary routine of the winds and weather in these latitudes often corresponds to the phases which are exhibited by the storms as above described, a correct opinion, founded upon this resemblance, can often be formed of the approaching changes of wind and weather, which may be highly useful to the observing navigator.

8. A due consideration of the facts which have been stated will inspire additional confidence in the indications of the *barometer*, and these ought not to be neglected even should the fall of the mercury be unattended by any appearance of violence in the weather, as the other side of the gale will be pretty sure to take effect, and often in a manner so sudden and violent as to more than compensate for its previous forbearance. Not the least reliance, however, should be placed upon the prognostics which are usually attached to the scale of the barometer, such as *set-fair, change, rain*, etc., as in this region, at least, they serve no other purpose than to bring this valuable instrument into discredit. It is the mere rising and falling of the mercury which chiefly deserves attention, and not its conformity to a particular point in the scale of elevation.

9. These practical inferences apply in terms chiefly to storms which have passed to the northward of the thirtieth degree of latitude on the American coast, but, with the necessary modifications as to the point of the compass which results from the westerly course pursued by the storm while in the lower latitudes, are for the most part equally applicable to the storms and hurricanes which occur in the West Indies and south of the parallel of 30°. As the marked occurrence of tempestuous weather is here less frequent, it may be sufficient to notice that the point of direction in cases which are otherwise analogous is, in the West Indian seas, about ten or twelve points of the compass *more to the left* than on the coast of the United States in the latitude of New York.

Vicissitudes of winds and weather on this coast which do not conform to the foregoing specifications are more frequent in April, May, and June than in other months.

Easterly or southerly winds, under which the barometer rises or maintains its elevation, are not of a gyratory or stormy character; but such winds frequently terminate in the falling of the barometer and the usual phenomena of an easterly storm.

Mr. Redfield stated it as his opinion that—

> The great circuits of wind, of which the trade winds form an integral part, are nearly uniform in all the great oceanic basins, and that the course of these circuits, and of their stormy gyrations, is, in the Southern Hemisphere, in a counter direction to those in the northern one, producing a corresponding difference in the general phases of storms and winds in the two hemispheres.

In referring to general storms, Redfield, in 1834, ascribed—

> The ordinary routine of the winds and weather to the passage of rotary storms.

And in 1846 he stated that—

> The greater variations of winter temperature are shown to result from the passage of rotary storms with warm southerly winds in their front and cold northerly winds in their rear.

Here we find the first expressed knowledge of the mechanism of cold waves.

In defining cyclones, he wrote, in 1854:

> The term cyclone was first proposed by Mr. Piddington to designate any considerable extent or area of wind which exhibits a turning or revolving motion, without regard to its varying velocity or to the different names which are often applied to such winds. Thus all hurricanes, or revolving storms, may perhaps be considered as cyclones, or revolving winds. But it by no means follows that all cyclones are either hurricanes, gales, or storms. The word is not intended to express the degree of activity or force which may be manifested in the moving disk or stratum of rotating atmosphere

to which it is applied. It often designates light and feeble winds, as well as those that are strong and violent. The more inert and passive cyclones, which seldom gain attention, but which constantly occupy in their transit the greater portion of the earth's surface, appear to move in orbits or courses corresponding with those of the more active class which have been traced on the storm charts. In a broad view of the case, the constant occurrence and progression of the cyclones in various degrees of activity constitutes the normal condition of the inferior or wind stratum of the atmosphere, at least in the regions exterior to the trade winds of the globe.

Following in the footsteps of Redfield, Lieut. Col. William Reid, of the Royal Engineers, London, issued in 1849 a volume on The Progress of the Development of the Law of Storms and of the Variable Winds, with the Practical Application of the Subject to Navigation. In reviewing the work of Colonel Reid, the author of a pamphlet, Statistics and Philosophy of Storms, remarks as follows:

> His attention was first directed to the subject in consequence of his having been employed officially at Barbados in reestablishing the government buildings, blown down by the hurricane of 1831, in which 1,477 persons lost their lives in the short space of seven hours. In order to learn something of the causes and modes of action of these violent gales, he searched everywhere for accounts of previous storms, and was fortunate in meeting with the memoirs of Mr. Redfield. Impressed with the belief that Mr. Redfield's views were correct, Colonel Reid determined to verify them by making charts on a larger scale and laying down the different reports of the wind at points given in Mr. Redfield's memoirs; and the more accurately this was done, the more did the tracks approximate to those of a progressive whirlwind. But Colonel Reid was not content with thus revising, in a more accurate projection, the labors of his predecessor. He obtained from the admiralty the logs of British ships that had been navigating the hurricane region, and by combining the observations which they contained with those made on land, he was thus enabled to group the varying phenomena of different storms; to place beyond a doubt their rotary and progressive character, as described by Redfield; to ascertain that they derive their destructive power from their rotary force, and to confirm the sagacious conjecture of the American philosopher that the storms in the southern latitudes would be found to revolve in a contrary direction (namely, from left to right) to that which they take in the Northern Hemisphere.

Colonel Reid concludes his observations with the following rule for laying ships to in a hurricane:

> That tack in which a ship should be laid to in a hurricane has been hitherto a problem to be solved, and this one which seamen have long considered important to have explained. In these tempests, when a vessel is lying to and the wind veers by the ship's head, she is in danger of getting stern way, even when no sail is set, for in a hurricane the wind's force on the masts and yards alone will produce this effect should the winds veer ahead; and it is supposed that vessels have often foundered from this cause. When the wind veers aft, as it is called, or by the stern, this danger is avoided, and a ship then *comes up* to the wind, instead of having to *break off* from it.
>
> If great storms obey fixed laws and the explanation of them given in this work be the true one, then the rule for laying a ship to follows like the corrallary to a problem already solved.
>
> In order to define the two sides of a storm, that side will here be called "the right hand semicircle" which is on the right of the storm's course as we look in the direction in which it is moving, just as we speak of the right bank of a river.
>
> The rule for laying a ship to will be: When in the *right hand* semicircle to heave to on the *starboard* tack, and when in the *left hand* semicircle on the *larboard* tack, in both hemispheres.

Espey made many valuable deductions in connection with the phenomena of the atmosphere. He maintained that the tendency of the winds in a storm is centripetal, because the primary cause of the movement is the low pressure at the center of the storm; and Redfield showed that the winds of a cyclonic system must have a whirling movement, because the rotation of the earth will inevitably cause such a whirl in any system of centripetal winds. Espey established "A qualified central tendency of the air in both the general storms and smaller tornadoes," and admitted that the deflective force arising from the earth's rotation is called on to cause and maintain a whirlwind:

> Upon the same principle, the tornado, the typhoon, and the widespread storm of the Atlantic, if the currents move toward a central point, must have a rotary character. In every such case the incoming of air must be regarded as a succession of rings taken off the surrounding atmosphere and moving slowly at first but swifter as they proceed toward the center. Each ring is affected by the law of deviation during its passage, and hence the ring begins to revolve when far from the center, turns more and more as it draws near it, and, finally, as it gathers about the central spot, all its forces are resolved into a simple whirl.

Following these pioneer discoverers and investigators of the character and nature of the new meteorology come Henry, Loomis, and Maury on the sea; and Ferrel, Blodget, Viñes, and Abbe have added valuable material by their studies and researches. The actual development of the science along useful lines began in 1843, when a grant of $4,000 was made by the legislature of Pennsylvania to the Franklin Institute for the purpose of establishing meteorological observing stations throughout the State. This was the first appropriation of public money made in this country for the collection of weather information. Referring to this work, the Philadelphia Bulletin of September 26, 1899, remarks as follows :

> The committee on meteorology of the institute, acting in conjunction with a similar committee from the American Philosophical Society, organized and equipped stations throughout the State and began the collection and preservation of data concerning weather phenomena. This work, it must be remembered, was carried on without the aid of the telegraph ; but it was so thoroughly done that from the data thus gathered was formulated a theory of storms which is substantially the same as that which is generally accepted to-day. This work was carried on for a number of years by the Franklin Institute ; in fact until, through the efforts of Prof. Joseph Henry, of the Smithsonian Institution, the attention of the Government was drawn to the matter. The interest thus aroused finally resulted in the organization of the Weather Bureau as it exists to-day.

The reports thus collected, with rather meagre telegraphic advices, made it possible to locate, plot, and determine the character of well-defined storms that traversed the region of observation. This system of reports was continued from the early fifties until the beginning of the civil war. In the meantime, and beginning with the introduction and attending the extension of the electric telegraph lines, the fact was noted, in the operation of the wires, that certain types of weather which were observed in the interior of the country usually passed eastward and were experienced in the Atlantic seaboard districts within periods which varied in length from one to three days.

After the war, interest in the subject of the weather was revived, and late in the sixties Prof. Cleveland Abbe, who has been associated with the Weather Bureau at Washington, D. C., since its organization, prepared daily weather forecasts for the Cincinnati Board of Trade, by aid of reports furnished through the courtesy of the Western Union Telegraph Company. The late Prof. I. A. Lapham, of Milwaukee, Wis., became actively interested in the subject, and, largely through his efforts, a bill, presented by the Hon. H. E. Paine, member of Congress from Wisconsin, was passed in the United States Congress in the early part of 1870, which provided for the establishment of stations of observation at a number of the more important cities upon the seacoasts and the Great Lakes, in the interior, and at military posts throughout the country. The act further provided that observations should be regularly taken at each of these stations, and that notice should be given by telegraph to lake and seacoast ports of the approach of storms of a destructive character. This work was assigned to Gen. Albert J. Myer, Chief Signal Officer, United States Army.

From the small beginning afforded by an annual appropriation of $15,000, the weather service rapidly assumed larger proportions and greater importance. The first marked advance in the direction of securing a more extended system of observations was, however, made in 1873, when, upon a proposition made by General Myer, the Meteorological Congress at Vienna adopted a plan which provided for simultaneous daily observations at noon, Greenwich mean time, in all the countries and upon all the navigated oceans of the world. These observations were continued from 1875 to 1887, inclusive, and were supplemented by a series of magnetic and meteorological polar observations from 1882 to 1884, taken by expeditions sent to the polar regions by the United States and the several European countries. The United States expeditions were sent to Lady Franklin Bay and Point Barrow, the Lady Franklin Bay expedition being under the command of General (then Lieutenant) A. W. Greely, Chief Signal Officer, United States Army, and the other under the command of Lieut. P. H. Ray. In addition, the cooperation of the regular naval and merchant marine services of the principal countries was secured.

In the fall of 1886 the writer, under the direction of General Greely and Col. H. H. C. Dunwoody, began the preparation of charts and tabulated and text matter summarizing the observations of this series. In 1893 this work was published as Weather Bureau Bulletin A, Summary of International

Meteorological Observations. A number of the charts of this bulletin, which present tracings of West Indian hurricanes from 1878 to 1887, inclusive, and additional data regarding the hurricanes charted, are herein reprinted and extended to include all hurricanes which have occurred since 1887.

During what may be termed the second period in the growth and development of this science many valuable contributions were made to the literature of meteorology. Conspicuous among the contributors were Prof. Elias Loomis, whose papers were issued from early in the forties until late in the eighties, and Prof. William Ferrel, who was probably the greatest of mathematical meteorologists. To Ferrel, in particular, are we largely indebted for our present knowledge of the phenomena of the atmosphere. He presented a masterful explanation of the planetary circulation of winds, and applied mathematical methods to the solution of the problems of the air. In his Essay on the Winds and the Currents of the Ocean, published in 1856, he wrote:

> The earth is surrounded on all sides by an exceedingly rare and elastic body called the atmosphere, extending with a diminishing density to an unknown distance into space, but pressing upon the earth with a force equal to that of a homogeneous atmosphere five and one-half miles high. It is also partially surrounded by the ocean, which is of a varying depth, and known to be, in many places, more than four miles deep. If the specific gravity of the atmosphere and of the ocean were everywhere the same, all the forces of gravity and of pressure which act upon any part of them, would be in exact equilibrium, and they would forever remain at rest. But as some parts of the earth are much warmer than others, and the air and water expand and become rare as their temperature is increased, their specific gravities are not the same in all parts of the earth, and hence the equilibrium is destroyed, and the system of winds and currents is produced.

Referring to the effects that are produced by this disturbance of equilibrium due to differences in heat, he remarked:

> All storms are produced by an ascending current of warmer atmosphere saturated with moisture, and this current is kept in motion by the continual rarefaction of the atmosphere above by means of the caloric given out of the water which is condensed as it ascends to the colder regions above. Therefore, as long as this ascending current can be supplied with air saturated with vapor this continued rarefaction must take place, and also the ascent of the air in the middle of the storm, and the consequent rush of air from all sides to take its place. If, then, all the lower stratum of atmosphere over a large district were saturated with vapor, without some disturbing cause, it might remain undisturbed; but if, from any cause, an ascending current is produced, either by local rarefaction of air by means of heat, or by the meeting of two adverse currents, which produce gyratory motion and consequent rarefaction in the middle on account of the pressure being taken away by centrifugal force, as soon as the air below, saturated with vapor, ascends to the colder region above, the vapor is condensed and the caloric given out continues to rarefy it so long as the ascending current is supplied with moist air. The surrounding cold air presses in below from all sides, and thus a storm of more or less violence is produced, moving with the general direction of the motion of the atmosphere where it occurs. The violence, then, of a storm, and also its duration, depends upon the quantity of vapor supplied by the currents flowing in below. Hence it is that the tropical hurricanes which originate in the Atlantic east of the Caribbean Sea do not abate their violence until they reach a high northern latitude where the atmosphere is cold and dry.

Aside from the investigations of Colonel Reid the literature of West Indian hurricanes is deficient in working facts until the last quarter of the nineteenth century. Preeminent among the workers of this period was the late Rev. Benito Viñes, S. J., formerly Director of the Magnetic and Meteorological Observatory of the Colegio de Belin, Havana. The investigations of Father Viñes are embodied in a paper published as Weather Bureau pamphlet No. 168, 1898, entitled Cyclonic Circulation and the Translatory Movement of West Indian Hurricanes. The conclusions of Father Viñes may be summarized as follows:

LAWS OF CYCLONIC CIRCULATION.

The aerial currents in a cyclone constitute a vast whirlwind around a central space of calm, of relatively small extent, called the "vortex" of the cyclone. It is an established fact that the direction of the rotary motion is always alike in the same hemisphere (northern or southern). In our own the cyclonic rotation is invariably from right to left, in the direction from east to north to west to south, or as commonly expressed, in a contrary direction to that of the hands of a watch placed upon a horizontal plane, face upward. In the Southern Hemisphere the cyclonic rotation follows an opposite direction.

In the West Indian cyclones the rotation and the cyclonic circulation takes place in such a manner that the inferior currents, as a rule, converge more or less toward the vortex; at a certain altitude the currents follow a nearly circular course, and higher still their course is divergent. It is particularly to be noted that this divergence is all the greater as the currents occupy higher altitudes until a point is reached where the highest cirrus clouds seem to move in a completely divergent radial direction.

The writer is prompted to question the accuracy of the conclusion of Father Viñes regarding a divergent radial direction of cyclonic currents in high altitudes. That the lower currents converge toward the vortex is an established fact; that the high upper currents have a divergent radial direction has not been established. Upper air cyclonic observations have been made only through an observance of cloud forms and cloud movements. These observations have shown that the different forms of cirrus clouds are carried by the controlling upper main current to the front, or in advance, of a cyclone; they have not shown that the clouds are projected *back* from the vortex. As a matter of fact the vortex acts as a chimney for the inflowing lower currents, and the moisture of these currents which is condensed into cirrus clouds in high altitudes, is carried forward like smoke which emerges from the top of a chimney.

The following rules are given for the approximate determination of the bearing of the vortex of a hurricane by using the direction of the wind:

1. When the vortex lies at a greater distance and the cyclonic winds are not yet well established, their convergence is apt to be greater and they are liable to many irregularities and to local influences.
2. The first squalls in front of a storm give divergent gusts. The squalls in fact proceed from the left-hand extremity of the cloud bank and their gusts are directed outwardly, as happens with the ordinary thunderstorm; hence, during such squalls the wind veers to the right, that is to say, toward the cloud bank, by four, six, and sometimes by eight points.
3. In the interior of the storm the gusts of the squall always bring the wind round to the right and therefore tend to lessen the convergence of the wind and sometimes almost to annul it.
4. As the wind increases in violence in the neighborhood of the vortex its direction becomes less convergent, owing to the centrifugal force developed in that part of the storm, and probably also to the influence of the incessant squalls which, in that part of the hurricane, continually occur.
5. In the Island of Cuba cyclonic winds blowing from north to north-northeast present scarcely any divergence at all; hence, in this particular case the law of storms[1] may be applied without notable error.
6. The trade wind, reinforced by the cyclone, modifies considerably the convergence of the cyclonic winds, sometimes (as in the above instance) suppressing it completely, and at others increasing it, so that the vortex may be lying to the south while the wind is from the northeast.

CLOUD MOVEMENTS.

The low clouds move in a direction nearly perpendicular to the bearing of the vortex.

The alto-cumulus, the dense cirro-stratus, and the light cirro-cumulus move from divergent directions, forming, with the bearing of the vortex, acute angles that are smaller in proportion as the currents to which they belong occupy a higher position; that is to say that the smallest angle is formed by the cirro-cumulus and the widest by the alto-cumulus; the intermediate angular magnitude corresponds to the cirro-stratus or the dense veil of cirrus clouds.

The light cirrus clouds constituting the highest current that falls under our observation move, as a rule, in a completely divergent or radial direction, forming with the bearing of the vortex an angle equal to zero, or practically inappreciable. This current is one of the most regular, and generally forms a right angle with that of the low clouds.

To sum up briefly, we find that the cyclonic currents which exhibit the greatest regularity and point out best the bearing of the vortex are those of the cirrus and of the low clouds. The current of the cirrus clouds is that which should be selected in preference when the first indications of the approach of a cyclone are seen and the vortex is still far distant. In the interior of a storm the observer must be guided principally by the movement of the lower clouds. In the absence of cirrus clouds, the currents of the cirro-cumulus and cirro-stratus may guide one, and when there are no lower clouds the wind and the high cumulus may be resorted to instead, always bearing in mind, however, that these indications are less reliable and the approximate inferences less satisfactory. In a well-developed cyclone of considerable intensity we can generally observe the following gradation and disposition of currents. If the vortex lies to the south-southeast, the cirrus clouds will move from south-southeast, the cirro-cumulus from southeast, the dense cirrus-veil from east-southest, the alto-cumulus from east, the low clouds from east-northeast, and the wind from northeast.

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[1] The author refers to the circular rule of the older cyclonologists, according to which the bearing of the vortex is eight points or 90° to the right if one faces the wind.

In the rear of the storm and, in general, when the prevailing winds are from the south, or from the points of the compass between east-southeast, south, and west-southwest, it is observed that all the currents in general form wider angles with the bearing of the vortex than in the previous case, the gradation between them, however, remaining the same. So that in the rear of the storm the inferior currents are more convergent and the superior ones less divergent than in the front. Thus, if the vortex, for example, lies to the northwest, the wind comes from south-southeast or south, the low clouds come from south or south-southwest, the alto-cumulus from southwest, the cirro-stratus from west-southwest, the cirro-cumulus from west, and the cirrus approximately from west-northwest.

Reference to the laws of cyclonic translation given in Father Viñes work can be omitted in favor of the very complete data regarding the movement of hurricanes which form a part of this paper. From the laws given, Father Viñes deduces, however, the following interesting conclusions:

That while every cyclone in August crosses the twenty-third parallel, the laws do not tell us that none of these cyclones pass near Havana, which lies precisely in latitude 23°. From them we also infer that, generally speaking, every cyclone in October crosses the eighteenth parallel in a certain direction, but they do not inform us that it very rarely happens that an October cyclone passes near Puerto Rico, which lies in that very latitude. Nevertheless, the fact exists, and is of such ancient belief that the ecclesiastical authority, from time immemorial, wisely ordained that priests in Puerto Rico should recite in the mass the prayer "Ad repellendat tempestates" during the months of August and September, but not in October, and that in Cuba it should be recited in September and October, but not in August. All of which proves that the ecclesiastical authority knew by experience that the cyclones of October are very much to be feared in Cuba, but not those of August, and that in Puerto Rico, on the contrary, the hurricanes of August are disastrous, while those of October are rare. This constant and well-established rule, proved by experience, implies a general law which connects the geographical position of the tracks on the map of the West Indies with the circumstance that the season is more or less advanced.

The formation of hurricanes is discussed by Father Viñes as follows:

It must, of course, be admitted that the tropical cyclones do not form indefinitely at any point within the tropical zones, but that they single out, in preference, for their formation and development particular and definite regions in those zones. The following geographical conditions generally, and in a more or less perfect degree, distinguish the cyclonic regions within the tropics: Large continents lie to the west, indented by numerous gulfs and bays whose coasts run more or less northward and southward, with vast and extensive seas to the east, overspread commonly with numerous islands. Such, at any rate, are the features that in a more or less perfect degree concur in the cyclonic regions of the Philippine Isles and in the China Sea, in the seas of India, and also in the Southern Hemisphere in the region situated east of Africa, in the vicinity of the islands of Madagascar, Mauritius, Reunion, Rodriguez, etc. But of all the cyclonic regions within the intertropical zone the one which more perfectly and grandly combines all these conditions is the great Bay of North America, with its wide Atlantic Ocean extending to the east as far as the coast of Africa, and to the northeast as far as the coast of Europe and the northern seas. In my opinion this contributes much to the grandeur and regularity of the immense paths of the West Indian cyclones. A cyclone of August or September may form in the vicinity of the Cape Verde Islands, near the coast of Africa, or to the east of the Lesser Antilles, cross the Atlantic along the first branch of its track, and recurve either in the Gulf of Charleston or on the coast of Texas. In the latter case it may cross the United States in the direction of Cape Hatteras, sweep, with renewed strength, and velocity, a second time across the Atlantic, in a northeastward direction, and enter Europe or be lost in the northern seas. We have, then, a series of cyclones which describe immense tracks over many thousands of miles with admirable regularity and normality, and subject to general laws. This is truly surprising and astounding. I do not believe that on the face of the globe there is another region where cyclones are met with that can compare with those of the West Indies, or, rather, I should say, with those of the great Bay of North America. Neither is there within the whole intertropical zone a grander bay than this one, nor one which offers more favorable conditions for the development and onward progress of gyratory storms.

The Bay of North America comprises, as I understand, that part of the Atlantic to the west of the fifty-fifth meridian (longitude west of Greenwich) from Newfoundland to Dutch Guiana. It is bounded on the east by the said meridian, and on the north, west, and south by the coasts of Newfoundland, Labrador, and Gulf of St. Lawrence, by the coasts of the Atlantic, Gulf of Mexico, and Caribbean Sea from Yucatan to Dutch Guiana. It embraces the West Indies, the Carribbean Sea, the Gulf of Mexico, the Bahamas, the Bermudas, and the gulfs of Charleston and of the St. Lawrence.

Now, it is in the southern part of this great bay, that is to say, in the Carribean Sea, and in that portion of the Atlantic which extends to the east of the West Indies, that hurricanes are formed and developed, with this peculiarity, that according to the position occupied by the equatorial zone of calms, by the Atlantic anticyclone, and consequently by the southern limit of the trade wind, respectively, the cyclones form either more to the south, and above all more to the east or west. The point of origin and formation of the hurricane depends, therefore, on the more or less advanced season of the year. Now, as the variations in the point or region where cyclones originate during the hurricane season principally affect the positions in longitude extending across the Atlantic from the Cape Verde Islands to the coasts of Honduras and Yucatan, and to the eastern portion of the Gulf of Mexico, it results that the region where the cyclones originate during two months and a half, that is to say, from the middle of August (maximum of cyclonic activity and of the recurving latitudes) to the end of October, or from the beginning of June to the middle of August, will move in the space between the Cape Verde Islands and the western portion of the Caribbean Sea.

According to my opinion this seasonal change of origin takes place in the following manner: In the middle of August, when the anticyclone of the Atlantic is about latitude 30° or 35°, the trade winds of the Northern Hemisphere and those of the Southern (converted into southwest monsoon) generally meet somewhat to the south of the Cape Verde Islands, where lies the area of low barometer, and in this vicinity it is that the August cyclones are formed. At this time the isobars of the Atlantic anticyclone extend to the southwest of the Island of Cuba and Caribbean Sea, and on this side no cyclones are formed. In the month of September the Atlantic anticyclone draws near Africa, its isobars invade the eastern part of the Atlantic east of the West Indies, and leave the Caribbean Sea free; at this time the cyclones are formed somewhat to the east of the Lesser Antilles or in their vicinity. In the first decade of October the state of things varies but little. Some cyclones, however, form rather more to the west in the eastern part of the Caribbean Sea. In the second and third decades of October the 30-inch isobar, which surrounds the Atlantic anticyclone and that of the American Continent, only leaves free the western portion of the Caribbean Sea south of Cuba and part of the Gulf, the depressions or low barometric areas move to this region, and it is here that the hurricanes originate which prove so disastrous to the western half of the Island of Cuba at this season of the year.

The months of June and July in this particular do not quite agree with those of September and October. In some years the anticyclonic isobars of July invade the Carribean Sea, and in those years there are usually no cyclones in July. In other years the anticyclonic curves lie rather farther north and leave the Carribean Sea free; in such years the cyclones are apt to form in those regions and follow the same laws as those of September, with the exception that they move in somewhat lower latitudes.

The hurricanes of the second and third decades of June agree with those of the first and second decades of October, respectively. Those of the first decade of June are very few; they come from the windward, move in very low latitudes, penetrate Mexico, and dissolve without recurving. Many years pass without cyclones in June; nevertheless, cyclonic purturbations following the same laws sometimes occur to the south and southwest of Havana, causing great inundations in the western provinces of Cuba.

In a pamphlet issued in 1890, Father Viñes gives the following interesting description of the characteristic phenomena of tropical cyclones, or West Indian hurricanes:

In a measure, as the barometer in its decided and continued fall announces the approach of the hurricane, and long before the cirro-strata appear there is a notable change observed in the atmospherical regions. The higher layers lose their extreme transparency and the blue of the sky is not so pure as before. A thin veil, scarcely visible, covers the celestial arch and it darkens by degrees; this hazy veil has the property of decomposing rapidly the solar light, giving passage in preference to the red and absorbing almost entirely the remaining rays whenever these solar rays, striking obliquely, are compelled to cross a large portion of the atmosphere. From this decomposition of the light there arises during this phase a singular and characteristic appearance of the sky during the rising and setting of the sun.

The atmosphere in the upper region takes on such occasions a uniform, reddish tint, which covers the whole hemisphere, and which, during the twilight and while the crepuscular rays are fading, merges into the dark red and somewhat violet color, which color remains a long time after sunset, as if this dim and prophetic light tried to prolong the evil omen in the longer duration of the twilight.

The head of the cumulus and strato-cumulus appear crowned with vivid and dazzling reflections, the violet color predominating at the base; objects appear colored with flaming reflections and the sky presents, as a whole, magnificent contrasts and beautiful pictures impossible to describe. Later, at the time when the cirro-strata begin to appear and the opaline veil becomes each moment more defined and transformed by degrees into a milky, semitransparent veil, these reddish tints take a character somewhat alarming as they obscure the sun; the whole atmosphere then simulating the glowing reflections of an aurora borealis which resembles an immense fire; and while the sun is dropping toward the horizon the colors gradually diminish in vividness, and I should compare them in this case to the dark red color of incandescent metal. The heavens acquire at this moment an appearence truly threatening and foreboding evil. These characteristic tinges have been compared by some authors to red copper colors and by others to red brick dust.

This phenomenon, as it is seen, is a constitutional physical result of the hurricane, a characteristic phenomenon, and as such it is never missing nor can ever be missing in a hurricane, and in a greater or less degree will also be observed in whirlwinds at various points of the globe and in very different latitudes, so that there can hardly be found a meteorological author who does not attempt a description of this phase.

Dr. Enrique del Monte, member of the Havana University, has furnished for the exclusive use of the Weather Bureau a very interesting paper on the Climate of the West Indies; and West Indian Hurricanes, their Origin, Courses, and Indications of their Approach. That portion of the paper which relates to West Indian hurricanes is as follows:

Hurricanes, in the general sense of the word, have always belonged to the number of those physical phenomena that have most attracted the attention of men, both vulgar and scientific—the former because they find themselves overtaken and terrified by the awful magnificence of the storm, and the latter, because to these and natural causes, they unite chiefly the sentiment of philanthrophy, and their perpetual ambition of the absolute control of the science.

In the scale of power or destructive strength of these phenomena, one of the most conspicuous places, beyond doubt, belongs to cyclones, which, as it is well known, are gigantic eddies of extraordinary violence. Furthermore, among those, the typic tropical cyclone, or West Indies hurricanes, are the most terrible and severe.

Hence, the activity displayed in Cuba in the last twenty years, leading to the practical study of this phenomenon and the advancing of its theory, and hence, too, the valuable works published by the late Professor Halkzenbrich, of Havana, member of the Royal British Meteorological Society, and a correspondent in Cuba of the Observatoire Meteorologique de Montsouris, France, the late Rev. Father B. Viñes, S. J., of the Royal College of Belen, at Havana, and those, more modest, but no less enthusiastic, of the author of this pamphlet.

And if the practical knowledge of the phenomena, invariably preceding by two, three or more days, the passing of a cyclone through a place, is always useful, it becomes necessary in the tropics, and chiefly so in the ***autumnal equinox.*** So that in the brief review we intend to make of such phenomena, we shall describe them to the reader in the same order of succession as they appear to the observer. This is called, in technical language, ***different phases of a cyclone at a distance.*** These phases follow one another with more or less rapidity, according to the position and velocity of translation of the hurricane.

What a cyclone means.—Before entering upon the description of the phases above referred to, we will say something about what may be called the *structure of a cyclone.*

What is a cyclone, aside from its origin?—The cyclone, and especially the tropical cyclone, is characterized by a vast eddy, on an average 300 miles in diameter, of extraordinary violence in the gusts of wind (90 miles per hour, and sometimes more) and carrying, necessarily, with it a *relative vacuum,* which increases from the periphery to the center or vortex. This rarefaction of the air in so large an area implies a lack of equilibrium in the atmosphere, which, by the *law of compensations,* represents affluence of air in one or more isolated places surrounding the hurricane.

Therefore, if we suppose the barometer (which is only a delicate balance, enabling us to weigh the atmosphere at any moment), to be situated in any place embraced from the periphery to the center or vortex of the eddy, the nearer it is to the vortex the lower its column will be.

On the other hand, let us suppose the barometer situated beyond the body of the hurricane, but as near as it can be without the observer being able to perceive any sign of the storm, there, in compensation for the relative vacuum that makes an integral part of the neighboring hurricane, will be, as stated above, an affluence of air, and, consequently, the barometer will rise more or less, but higher than the normal, and in some places it reaches an extraordinary maximum.

The above-cited affirmation that the hurricane is characterized by a relative vacuum seems a paradox at first, since the testimony of our senses tends to evince to us the contrary, in the unusual impetuousness of the winds, to such an extent that the existence of a hurricane is physically impossible without the wind having at least the velocity of a strong gale. This contradiction disappears if we have in mind what the wind means. In fact, the wind is only a mass of air that runs with more or less violence to a point in which, by any cause, a relative vacuum has been formed. From the gentle breeze, walking two miles an hour, to the furious gale, running 100 miles, all the wind velocities are subordinate to the above-cited general cause.

In order to explain to ourselves graphically the physical reason existing between the velocity of a gentle breeze and that of the furious gusts in a tropical hurricane, let us suppose an extent of ground 60 miles long, and let us suppose, too, five observers, provided with standard barometers and situated 12 miles apart, respectively. Now, let them take simultaneous observations at a preconcerted hour (10 o'clock a. m., for instance), and correct them for temperature and elevation. Everyday experience demonstrates that the larger the difference between the readings of the barometers at the stations, the greater is the velocity of the wind at that moment. These differences of readings in simultaneous observations are called in meteorological language barometrical gradient. The lines on the surface of the globe connecting places that present the same barometrical pressure at any moment are called isobarometric.

And now a very interesting point here arises: Is there any constant relation between the magnitude of the barometrical gradient and the wind's velocity all the world over? In other words: To a given gradient—for example, 0.10 millimeters per mile—does the same velocity of the wind always pertain, regardless both of the latitude of the place and the season? We firmly believe that latitude has a very notable influence in this matter, as well as topographical conditions and seasons.

Barometrical gradients and their features in Cuba.—Regarding the Island of Cuba, which has for a long time been the field of our investigations in everything leading toward the knowledge of its climatology, we can affirm, by reason of repeated experiments, that whenever the barometrical gradients amount to 0.04, 0.05, and 0.07 millimeters per mile, the *mean* velocities of the wind, approximately, are 15, 30, and 45 miles per hour, respectively. We say approximately, because the given numbers are the average of the different months, the velocities of the wind corresponding to every gradient being a little higher in summer than in winter.

During the passage of tropical hurricanes through the island, when the *mean* velocity of the wind is generally 65 miles per hour, we have always endeavored to investigate the relation between the barometrical gradients and the wind velocities, without ever being able to find any satisfactory result; owing, in our opinion, to the irregular and rapidly variable isobarometric distribution. This irregularity, more or less apparent, always exists in the dominions of the hurricane; occasioned by the intermittent, frequent, and copious condensations of the aqueous vapor, affecting locally in this way the vertiginous and powerful ascending currents.

Herefrom arise the two following, and nearly insuperable, difficulties, hampering greatly the measurements of the gradients:

1. Rough and frequent oscillations in the barometric columns, ranging from 0.50 to 0.80 millimeters, (every five seconds on an average), thus making it impracticable to take an exact reading of the pressure of the air.
2. A continuous variation in the wind velocity, that passes, in a few seconds, from a fresh breeze of 25 miles per hour, to the most violent and furious gale of 90 and 100 miles.

So that in order to be able to find in such an anomalous condition, any relation between the gradients and the wind velocities, it would be necessary to have the stations located at very short distances, respectively, perhaps no farther than one mile apart, and also to have all the barometers and anemometers connected with the central station by means of the electrical registers at a distance, where the indications of all of them should be taken simultaneously on a special *Chronographic* cylinder.

As a valuable proof of the exactness of this affirmation, we will cite a practical case which occurred during the passage of a cyclone through the island.

On the 21st of October, 1895, at 10 h. a. m., the vortex of the hurricane was, approximately located, in latitude 23° 00′ N., and longitude 79° 00′ W. from Greenwich; that is to say, about 30 miles to the northeast of Sagua La Grande. At that moment the barometrical pressure at Havana was 752.30 millimeters, or 29.62 inches; and at Matanzas, (practically the nearest station in the line of the gradient; situated about 55 miles E. ¼ southeast from Havana), at the same moment, (10 h. a. m., 82° 21′ meridian time), the pressure was 748.45 millimeters, or 29.47 inches. We had, therefore, a *gradient*, amounting to 0.07 millimeters per mile, approximately. To this *gradient*, according to repeated experiments, should pertain in normal weather conditions in October, a velocity of the wind of about 48 miles per hour. Notwithstanding this, the anemometer in Havana showed a mean velocity of 56 miles an hour. Such an anomally we can only attribute to the above-cited causes.

In several previous hurricanes, of different destructive strength, all attempts to compute the gradients have been thus far unsuccessful.

We shall now begin to examine the different phenomena, all closely connected, which always indicate the existence of an atmospheric disturbance. The careful observation of these phenomena will not only enable the observer to detect the disturbance, where its vortex is on an average 1,500 miles away, but will also, in most of the cases, allow him to judge about its magnitude and intensity.

As we said in the introduction, in this brief review we shall present them to the reader in the same order of succession as they appear to the observer; saying then, also, that in technical language they are called: *different phases of a cyclone at a distance.* We also pointed out in the introduction above referred to that by what may be called the mechanism of the hurricane itself, the great rarefaction of the air, attending the eddy, implies a fault of equilibrium in the atmosphere; which, by the law of compensations, represents affluence of air, more or less perceptible, in the vicinity of the hurricane; the barometer reaching in two or more isolated places an extraordinary maximum.

First phase of the hurricane: the anticyclone.—Hence, we have already the first phase of the hurricane; and when its vortex is on an average 1,500 miles off. This phase is called the *anticyclone.* As its name indicates, it is the reverse of the cyclone. In fact, the meteorological elements follow in it a course different from the normal, and quite different, too, from that in the dominions of the hurricane.

Its distinctive features are the following:

1. An anomalous rising in the barometer. It reaches sometimes an exaggerated maximum.
2. Fine and rather cold weather. The temperature goes, on an average, 14° F. below the normal.
3. Cloudless sky, and of a decided indigo blue. Consequently in this kind of weather, the dew-point and relative humidity are always far below the normal.
4. Persistency of the *anticyclonic winds.* That is to say, the daily shiftings from the land to the sea breezes, and vice versa, disappear entirely, or at least, are greatly disturbed.

5. Different order in the circumgyration of the atmospheric currents from those in the hurricane. In the anticyclone the gradation is from right to left, beginning from the lowest current.

Summing up we will say, that all the anticyclones that may appear to the observer, presenting the features above referred to, always indicate *á priori* the existence of an atmospheric disturbance. In the Island of Cuba, when they appear in the months of cyclonic activity, they must be always carefully observed and studied, as their subsequent positions may furnish the observer with valuable information regarding the hurricane. On the other hand, when their appearance takes place in the months of *calm in the cyclonic activity*, they pertain to hurricanes of high latitudes, although in some instances, as we shall see in the next section, they may offer some dangers to navigation, through the northern Cuban coasts.

Some features of the anticyclonic weather in Cuba.—We will now refer to some weather features in the Island of Cuba, when it happens that the anticyclones bear in some peculiar positions in relation to the island. As these features of anticyclonic weather, of which we are about to speak, are very different from those described in numbers 2 and 3 of the last section, we may properly assign them as exceptions to the general rules.

FIRST EXCEPTION.

Regarding Havana and its vicinity, the only exception we know to the characteristic features of anticyclonic weather, described in numbers 2 and 3 of the last section, arises when the anticyclones bear northeast from the city, in the months of November, December, January, February, March, April, and May. In these cases the weather is cloudy and showery, owing, we believe, to the collision of the anticyclonic upper winds (in the months very dry and cold), with the upper atmospheric general current, that all this time, invariably comes from the west-southwest, always abounding with the heat and dampness of those regions. This class of anticyclones never precede the tropical hurricanes in the Island of Cuba, as the above-mentioned months are those of calm in the cyclonic activity. So that when they appear northeast from Havana they always pertain to hurricanes crossing the Atlantic, and whose vortices lie between forty-five and fifty degrees of latitude. On the other hand, when the anticyclones bear northeast from Havana, in the hurricane season, namely: June, July, August, September, and October, then the weather appears, as has been described in numbers 2 and 3 of the last section, owing, in our opinion, to the following causes:

In the months of cyclonic activity the upper general current goes higher than in the remainder of the year. The average altitude of the upper cirri in these months is a little higher than the figures given by Dr. Vettin, of Berlin. Therefore, the intrusion, or interchange, of this current with those of the anticyclone, is very difficult if not impossible. But assuming such an interchange not to be so difficult as we believe, the thermic and hygrometrical conditions of both currents are not so different in these months as in the others.

Besides this, in the months of cyclonic activity, the upper general current is subjected to the interesting changes fully described in the first part of this work. Those changes tend also to render difficult the collision of this current with those of the anticyclone.

SECOND EXCEPTION.

Here we wish to refer to a noteworthy feature, occurring in one section of the north coast of the island, embracing from Sagua la Grande to Bahia Honda (and singularly remarkable in Havana), when it happens that the anticyclones bear north-northwest, north, or north-northeast from that section.

It is a well known fact that this section of the Cuban coast is generally subject to high winds and ruffled seas.

The daily maximum velocity of the wind in Havana takes place between noon and 4 h. p. m., being on a yearly average 11.5 miles per hour, (mean velocity); and the daily absolute maximum velocity, counting the revolutions of the anemometer in one record of time, averages yearly 17.5 miles per hour.

In order to have the daily absolute maximum velocity accurately determined, the Central Observatory was furnished with an anemo-cinemographe, of the manufacture of Richard Frères, of Paris. This instrument is carefully described in the pamphlet "Notice sur les instruments enrégistrés construits par Richard Frères; Paris, 1889," page 51.

But in the particular case of which we are speaking, namely, when the anticyclones bear north-northwest, north, or north-northeast from that section of the coast, the trade wind (whose daily absolute maximum velocity is, as above said, on an average 17.5 miles an hour), often increases to 40 and 45, and sometimes to 50 miles an hour. These high winds and gales are always attended by very heavy and dangerous seas, so that the captains in those waters must be always watchful and ready, as this rough weather, in many cases, cannot be accurately forecast so long as the island lacks valuable information regarding the weather on the American Continent. This kind of weather is the most awful to the seamen, as it is apt to appear and wage destruction, notwithstanding the high barometer and cloudless sky.

Many ships are driven ashore every year by this kind of weather, and in some instances with fatal consequences, resulting in their total destruction. Three miles eastward from Morro Castle, in Havana, along the rocky shore, lies the iron hull of the American steamer *Hutchinson*, of the New Orleans Morgan Line. A gale drove her ashore five years ago, and her hull remains there as a silent warning to the seamen. A few months after this disaster the big Spanish steamer *Cadiz* met the same fate not far off from the *Hutchinson*. Again, three years ago, the Spanish gunboat *Christobal Colon* went ashore, and was completely wrecked, one mile from Bahia Honda. We could refer to many accidents of this kind to big ships. To number the casualties among the smaller vessels would be almost impossible.

Second phase of the hurricane: Mean zones or intermediate spaces between the anticyclone and the cyclone.—Soon after the observer is getting rid of the influence of the anticyclone, while on the other hand the approaching hurricane is still far enough away to prevent its detection, the following phenomena are generally noticed:

1. The barometer begins to fall slowly. Irregularities and fluctuations in its column are always noticed owing to the antagonizing influences exerted on it.
2. The appearance of the sky is highly changeable, passing sometimes, in a few minutes from entirely clear to cloudy, and vice versa.
3. Consequently the temperature and moisture of the air are also very fluctuating.
4. The wind directions in the different atmospheric strata are singularly unstable. We have frequently observed the passing of those currents, in a very short time, from anticlyclonic to cyclonic, and vice versa.

All the above weather features are always more or less perceptible under atmospheric cyclonic conditions, and after the gradual recession of the anticyclone. The brightness of this phase obviously depends on the power exerted by both the anticyclonic and cyclonic systems as well as in their relative position to the observer.

Third phase of the hurricane: Changes and phenomena to be observed in the upper strata of air.—This phase begins when the anticyclone in its progressive motion is so far away as to be imperceptible to the observer, while the hurricane is gradually approaching him.

Hitherto we have examined what may be called deductive methods of ascertaining the existence of the hurricane. We will now study what may be called inductive methods. In fact, under the heads "First and second phase of the hurricane," we have examined those phenomena whose operations, if closely connected with the hurricane, take place beyond its limits. On the contrary, the phenomena upon whose study we now enter are originated in the body of the hurricane itself.

Alteration of the light in the upper strata of air. Reddish and ruby skies.—This phenomenon is always noticeable when the outermost part of the hurricane begins to invade the place of observation. The unsettled weather, described in the last section, gradually disappears and the barometer falls now steadily but rather slowly. By this time the transparency and blueness of the sky, characteristic of the past anticyclonic weather, is succeeded by an opaqueness or veil called cirrhose veil, so extremely subtle in the beginning as to render it almost imperceptible. Notwithstanding its subtlety this veil exerts a very great dispersive power on the solar rays; its principal feature being the almost entire absorption of all the prismatic colors, except red. These dispersive and absorptive powers are singularly remarkable when the solar rays are compelled to pass through a great portion of the atmosphere. Consequent upon this the sun's rising and setting are attended by an anomalous reddish coloration in the sky ending or beginning, accordingly, when the sun's altitude is, on an average, 15°, the coloration increasing as the altitude decreases.

B.—Precursory cirri and their magnificence. Invaluable data to be derived from their appearance.—Just here the observer is confronted with the most splendid phenomenon to be observed in tropical meteorology.

Soon after the reddish coloration is noticed the tribe of cirri makes its appearance. These clouds are oftentimes called "Pele's Hair," "Mare's Tails," etc., on account of their fibrous or filiform structure. As is well known they resemble in their form a feather or plume of highly variable dimensions.

The appearance of these clouds shows an organization whenever pertaining to tropical hurricanes, seldom noticed, if not unknown, in those attending high latitude storms. In fact during our long stay in New York, N. Y., we have had ample opportunity to watch a good many specimens of cirri in connection with storms of very different energies, having utterly failed in detecting any similitude with those frequently observed in the West Indies hurricanes.

The shape of the typical tropical cirrus is that of a most perfect and remarkably beautiful feather or plume snow-white, in which the shaft or stem is of a fibrous structure, great density, and averaging 80° in angular length. The vanes are equal and closely distributed on both sides of the stem, being of filiform structure, divergent, and of marked outward curvature.

It is also noticeable in connection with these clouds that when there are two or more, as is usually the case, all of them agree in their directions, converging to a given point on the horizon. This point is called divergence focus.

Whenever these cirri are carefully observed a great activity or instability is always detected as taking place in their masses. So their longitudes are frequently seen, increasing or diminishing, in a short space of time.

In spite of this instability the cirrus is never deformed nor deflected from its primitive direction.

By this phenomenon positive evidence is obtained that whatever may be the operations going on in the clouds, the facts remain:

1. That the powerful streams made transitorily visible through the condensing vapor are of very great steadiness in their directions.
2. That these streams are subjected to rather rapid changes in their energies.
3. That these changes are always accomplished with remarkable regularity as long as the cirrus is neither distorted nor deformed.

Such are, in brief, the characteristic features of the typical tropical cirri.

Let us see, now, the invaluable information to be derived from them regarding the coming hurricane.

Early in 1877, the Rev. Father Benito Viñes, S. J., from the Belen College, Havana, advanced the two following theories:

1. That the cirri crowning a hurricane show exactly, or very closely, to the observer, the direction of the radius of the hurricane; so that the divergence focus shows him the bearing of the vortex.
2. That in every hurricane the structure, appearance, and magnitude of the precursory cirri are always in close relation to the magnitude and energy of the hurricane.

Regarding these theories, we can only say that after having been, both of them, subjected to a most exhaustive series of observations, by Professors Halkzenbrich, Theyer, and ourselves (embracing more than fifteen years), we do not know of a single case in which the theories were not fully confirmed.

Tropical meteorology is thus in possession of a most valuable source of information regarding threatening hurricanes, while their vortices are, on an average, 600 miles off.

Father Viñes, purporting to bring into practical application his second theory, divided all the cirri into two groups, and then, selecting from each group its most characteristic form, obtained two specimens calling them extreme types.

Let us now examine the distinctive features of these types.—*First type.*—The shape of these cirri, often called the typical cirrus, is carefully described in this section.

This kind of cirri always pertain to the typical tropical hurricane: cyclone of short diameter, sharp barometrical gradient, and consequently, powerful ascending currents and extreme destructiveness. In these cases, the appearance of the precursory cirri takes place when the vortices are, on an average, 350 miles off.

Second type.—According to Father Viñes, this cirrus is characterized by its filiform structure, belt shape, and great extensiveness. It is frequently the case that the observer loses sight of it in opposite horizons.

When there are two or more of these cirri they appear like belts or zones parallel to their longitudes. M. Ch. Martins, in his translation into French of the Kaemtz's work, Paris, 1858, says: "La tendance qu'ont les cirrus à se disposer suivant des bandes paralleles entre elles est remarquable, et prouve que la cause qui dirige leurs filaments, suivant tel azimuth, plutôt que suivant tel autre, au lieu d'être simplement locale et accidentelle, s'étend à de grande distances."

According to Viñes, "The constituent matter of this cirrus is extremely attenuated, inasmuch as its appearance is always of a slight opaline color, dimming the sky in some degree without reducing at all its transparency." In fact, the appearance of this cirrus is like gauze or muslin, of a very subtile texture, resembling to that extent the tail of a comet. We have had ample opportunity to see through these clouds stars up to the sixth magnitude.

These cirri always belong to the upper general current, sometime called antitrade current. They pertain to the highest strata of air, where the currents, as shown by the shapes of these clouds, are of remarkable regularity, though subjected to the most interesting changes, which are fully described in the first part of this work.

Being already familiar with the two leading types of Viñes classification, the first of which belongs, as has been said, to the typical tropical hurricane, and the second to the perennial cyclonic tendency in the equatorial doldrums, we will now make a brief examination of the intermedial or transitional types from the first to the second, having in mind (and here lies the chief feature of Father Viñes' theory) that as the shape, appearance, and structure of the precusory cirri of a hurricane depart from the first type and approach the second in the same relation the hurricane's energy will always be minor, and sometimes no more than a slight cyclonic disturbance.

According to Father Viñes, the intermedial types are characterized by the following features:

1. Want of perfection and harmony in the whole of the cloud.
2. Greater length in the feathers, being only generally partially visible.
3. Lesser condensation in their masses.
4. Greater fineness and delicacy in their parts.
5. Augmentation of nebulosity in their middle.

In fact, the derivations of the first type generally appear assuming the shape of an imperfect feather, in which the lower part of the shaft is invisible, possibly because of its nonexistence or perhaps on account of its being located at a greater altitude than the vanes, and thus concealed behind the cirro-pallium. Sometimes these cirri appear in a still more anomalous shape, viz, a feather without shaft, the vanes being distributed at each side of the central empty space. Possibly, too, the shaft bears at a greater altitude, being also hidden by the cirro-pallium. But whatever may be the form, more or less perfect, of the intermedial types, they are always larger than those of the first type, of a minor condensation in their masses, and consequently less whiteness and reflecting power, filiform structure, and semitransparent vanes.

Summing up all the statements concerning the precursory cirri of a hurricane, we now derive the following conclusions:

1. Cirri of the first type on a blue sky, extraordinary whiteness and perfect shapes, great condensation and reflect-

ing power, lively activity in their masses, and strong divergence focus at a given point on the horizon; these cirri always belong to the typical tropical hurricane, viz., cyclone of short diameter, moderate altitude, sharp barometrical gradient, and extreme destructiveness. This kind of cirri generally appear to the observer while the vortices are 350 miles off.

2. Cirri of the intermedial types. These cirri always appear on a faint blue, nebulous sky, and always pertain to hurricanes of a greater diameter than the typical cyclones, greater altitude, moderate gradient, and consequently less destructiveness. The shapes of the intermedial types being so numerous and almost indescribable, it is very difficult to state here the precise relation between what may be called appearance and energy. Nevertheless, the following rule, we believe, may lead us far toward some practical results: *The magnitude and force of every hurricane is always proportional to the magnitude and perfection of the precursory cirri, as well as to the greater or lesser diaphaneity of the atmosphere attending their appearance.* Thus large cirri of truncated or irregular shapes, hardly discernible through a dense opaline veil, are always followed by cyclonic disturbances of a great diameter and altitude, gentle gradient, copious rains, and moderate winds from 40 to 50 miles per hour. In these cases the precursory cirri appear to the observer while the vortices are 700 to 800 miles off.

As a good practical illustration of the invaluable data to be always derived from the positions and appearances of the precursory cirri, we will mention a case occurring in the last hurricane investigated by our observatory: On the evening of October 18, 1895, we detected a hurricane bearing south-southeast from Havana, the only sign of it hitherto being a weak *focus of cirri* diverging from that point, very near the horizon, and attended by a slightly opaline sky, promptly turning into gay ruby colorations at sunset. By the structure, size, and appearance of the *cirri*, openly differing from those of the *first type* of Viñes, we concluded the hurricane was of moderate energy and common features. The position of the vortex at that moment (on the Caribbean Sea) was such as to prevent direct information regarding the storm. In fact, it was afterward verified that its vortex on that day was bearing south-southeast from Havana toward 16° north latitude. The track was directed to north-northwest, according to the normal tracks for that date; recurved between 21° and 22° latitude, in observance, also, of the recurving laws; and, after crossing through the central section of the island, gained the Atlantic at a point not far from Sagua la Grande. The absolute maximum velocity of the wind in Havana was 37 meters per second, or about 83 miles an hour, the barometrical minimum (reduced to sea level and 0° Centigrade) being 751.60 millimeters, or 29.59 inches.

In this hurricane the preceding anticyclone crossed at some distance from Havana, and we could not detect it, the first noticeable phase being the appearance of the precursory cirri on the 18th.

Solar and lunar halos, parhelia and paraselene, threatening skies.—Shortly after the appearance of the precursory cirri it is always noticeable that the subtile opaqueness, or veil, has gradually acquired density, and now resembles a light curtain of a milky appearance. During this phase the delicate filaments of the cirri are almost imperceptible, owing to the interposition of the veil.

Solar and lunar halos are always phenomena attending this kind of weather, the parhelia and paraselene being seldom noticed. At the beginning the halos are of a weak appearance; but later, and when the veil is still denser, they usually display extraordinary brilliancy, which afterwards gradually declines as the veil is changing to a dark cinereous color.

The reddish colorations attending the sun's rising and setting are now of a most indescribable and threatening appearance, resembling the resplendence of a bright polar aurora. The ruby color is gradually turning into crimson as the sun is reaching the horizon, and shortly after its setting the whole sky has the appearance of an enormous conflagration.

Cirrhose arc: its appearance.—While the cirrhose veil is increasing in density, as we have seen in the last section, it is always noticeable that at a given point in the horizon the condensation of the veil is greater. There the veil has the appearance of a segment of a circle at first, tangent to the horizon, but gradually rising to a maximum of perhaps 10° above. This arc is generally called the cirrhose arc. Its color at the beginning—that is to say, during the phase of which we are now speaking—is the same as that of the veil covering the whole hemisphere, only that the accumulation of vapors being greater where the arc appears, its reflecting power is necessarily greater; so that, in spite of the identity of colors between the cirrhose veil and the arc, the latter seems perfectly detached, a similar phenomenon to that always noticed in the tail of a comet, where the tail is brighter near the borders than along the middle, in spite of the uniformity in its color.

The point in the horizon at which this arc is formed always coincides with the divergence focus of the observed cirri, and therefore with the bearing of the vortex to the observer. In fact, the arc is but the visible upper part of the approaching hurricane.

Seamen navigating in tropical seas in the hurricane season must carefully observe if, after the appearance of the precursory cirri, the cirrhose arc is formed, attended by halos and reddish colorations, with falling barometer. In this case there is no time to be lost. Let them consult without delay the charts of normal tracks for the different months of cyclonic activity, and if they find themselves to be in a dangerous zone adopt immediately the measures they may deem necessary.

While the phenomena described have been taking place, the different atmospheric currents, of an unstable nature at the beginning, have been gaining regularity, and they are now quite cyclonic. These currents, in every tropical hurricane, appear to the observer to be making different angles with the bearing of the vortex, according to the height of the different currents, the gradation being expressed in the following table:

Different currents.	Angles with the storm radius, or bearing of the vortex.
	°
1. Wind direction or superficial current	112
2. Lower clouds (nimbus)	90
3. High cumulus	68
4. Cirro-stratus	45
5. Cirro-cumulus	22
6. Cirri	0

So that, assuming the vortex as bearing southward from the observer, the wind blows, approximately, from east-northeast; the *nimbus* come from the east; the *high cumulus* from east-southeast; the *cirro-stratus* from the southeast; the *cirro-cumulus* from south-southeast, and the *cirri* from the south.

It is to be noticed further that the angles assigned in the preceding table are only on an average, and pertain to the typical hurricane. Therefore, whenever the currents in the coming hurricane present exactly, or nearly, the above tabulated relation, the hurricane will be a typical one—short in diameter and of extreme destructive violence. On the other hand, if the currents make angles lesser than those expressed in the table, this being the general case, then the hurricane will be of usual or moderate violence. If it is noticed that currents 1st, 2d, and 3d, or 1st and 2d, or 2d, and 3d agree in their directions, then the hurricane is of defective organization and great diameter, sometimes being no more than a slight cyclonic disturbance.

Bar of the hurricane: its appearance. Data to be derived from its observation.—The cirrhose arc, described, gradually changes as the hurricane is approaching. At the beginning its color is of a whitish-milky appearance, but now its color is rather dark and opaque, soon to be turned into black. After this change in its appearance the arc is called the bar of the hurricane.

The bar has the appearance of an arc whose altitude in the horizon is generally from 10° to 15°. It is formed in its upper section by cumulo-stratus, and in the lower one by a nimbus of great size and black color. The base of the bar is always concealed below the horizon, so that *solution of continuity* is never detected between the bar and the horizon.

Showers and squalls: their phenomena.—Shortly after the bar is formed in the horizon the nimbus of the hurricane begin to overrun the skies with inexhaustible succession and high speed. Showers of short duration begin, and the wind velocity increases from that moment. The barometer that has been slowly falling since the beginning of the second phase, now drops abruptly.

It may be well to notice here that in every perfect hurricane of great or relative moderate intensity, the rain, at the beginning, is of a showery nature, attended by squalls from 55 to 65 miles an hour, while the mean velocity of the wind is from 35 to 40 miles. On the contrary, as the vortex approaches the rain is always continuous, although highly irregular, the showers succeeding each other at shorter intervals, and always attended by furious gusts of 100, 110, and sometimes 120 miles an hour.

As is well known, the energy of every tropical hurricane is always in close relation with the frequency and fury of the attending showers. It being always the case that the hurricanes *are fed*, and their *activity* maintained unabated by the characteristic showers which accompany them, by reason of the fact that this rapid upward convection contributes largely to a more and more severe precipitation.

The principal features accompanying the showers are the following:

1. Extraordinary increment in the wind's velocity at the beginning and during the shower. The mean velocity of the wind in the body of the hurricane is, on an average, 65 miles an hour, increasing then to 100, 110, and sometimes 120 miles, in the form of gusts, their duration ranging from 3 to 4 seconds. As the shower relaxes the wind abates, the duration of the showers being from 60 to 120 seconds.

2. At the beginning of, and during the shower, the wind's direction always shifts to the right (supposing the observer facing toward the wind) from 45° to 90°, so that if the wind was blowing before the shower, say from the north, during the shower, it will blow from northeast, east-northeast, or east, oscillating greatly in its direction, according to the frequency of the gusts, the greatest elongation corresponding *always* to the greatest fury of the wind.

3. During the continuance of the intermittant gusts (forming, as we have seen, a part of the shower), the barometrical column oscillates greatly, the amplitude being from 0.02 to 0.03, and sometimes 0.04 of an inch. This renders it very difficult to take accurate readings of the instrument.

Passing now to an examination of the characteristic features of the rains in the tropical hurricanes, we have the following results, derived from observations of a large number of cases.

1. In every tropical hurricane the area of rain extends *forward* to 150 miles from the vortex; while *backward* it only embraces 100 miles from the vortex, both distances being averages. Nevertheless, instances are on record in which the area of rain extended itself farther *backward*, or to the *right* or *left* of the vortex.

2. In cyclone disturbances of great diameter and large altitudes, the area of rain generally extends around the vortex, from 500 to 700 miles. In this kind of storms the rain is always copious and continuous, a procedure widely opposed to that followed in the typical hurricane, where the rain is always of a showery nature. Floods are the principal dangers and immediate results of these cyclonic disturbances.

The theory in favor with many conspicuous meteorologists, that *storm centers move toward the region where the greatest precipitation takes place, does not seem well confirmed in the process of tropical hurricanes.* As we have already seen, the tracks of the tropical hurricanes are in close relation with the course of the upper atmospheric current, and its periodic changes, the existence of what may be called *traced tracks* for the hurricanes (changeable with this current) for every period of the hurricane season or cyclonic activity, seeming thus a demonstrable fact. It is true that in most of the *tropical* hurricanes the area of precipitation extends itself more toward the front of the storm, and this fact seems to be a confirmation of the above cited theory; but there are the two following, and in our opinion powerful reasons, tending to embarass that theory, at least so far as the tropical hurricane is concerned.

1. Instances are on record in which the area of rain extended itself farther *backward*, or to the *right* or *left* of the vortex. 2. In cyclonic disturbances of great diameter and large altitude, the area of precipitation generally extends to equal distances around the vortex. In this, as well as in the former case, the storm centers always follow their normal routes.

Besides this, the deflection of the hurricanes of September 4-5, 1888, seems to confirm the theory advanced by Father Viñes, that tropical hurricanes are directed, or impelled in their tracks, by the upper atmospheric current.

The fact that in the tropical hurricanes the area of precipitation extends itself more toward the front of the storm, is in our opinion, purely a result of the mechanism of the hurricane itself. In fact, it is easy to conceive that inasmuch as the ascending currents come first in contact with the upper strata (always cooler than the lower strata) at the forepart of the eddy the upward convection of vapor thus accomplished, occasions the more copious and showery condensations at that point. In this way the forepart of the storm operates as a huge condenser, in which the ascending air frees itself of the greater part of its vapors. Continuing, the spiral ascending of this air comes in contact with still higher layers in the *rear* portion of the storm, and condensing there another part of its remaining vapors, occasions an area of showery precipitation, necessarily less abundant, and the area less extensive than in the forepart of the storm. Ascending still more, this air in the eddy comes again to the front, and the new condensing vapors occasion there the continuous drizzling rain, always attending the forepart of the hurricane, independently of the characteristic showers. Still continuing, the ascending air reaches again the rear of the storm, and there the condensing vapors result in the abundant formation of cirro-stratus and cirro-cumulus clouds, the drizzling rain being seldom noticed in this part of the hurricane. Coming again to the front, and reaching now a great altitude, the vapors of the air occasion the formation of the splendid cirri, crowning the hurricane. And a very interesting feature in connection with the cirri is that those at the rear of the hurricane always reach a greater altitude than those in the front, the former being detected about 410 miles from the vortex, while the latter are only discernible at 357 miles, both distances being averages. This seems to be conclusive evidence that the operation of the ascending air is as we have stated above.

The long and tedious procedure described in the last number may, we believe, be simply represented in the following table:

Phenomena occasioned by a volume of air ascending through the spirals of a tropical hurricane.

Passages by the front of the hurricane.	Passages by the rear of the hurricane.
First passage: Showers of great intensity.	First passage: Showers of moderate intensity.
Second passage: Continuous drizzling rain.	Second passage: Abundant formation of cirro-stratus and cirro-cumulus.
Third: *Cirri.*	Third: *Cirri*, at a greater altitude.

Observation of many tropical hurricanes leads us to conclude that the above-cited operation is either rigorously exact or, at all events, is not too far from the truth.

The fact that in some hurricanes and at some points of their tracks the area of precipitation extends itself farther *backward*, or to the *right* or *left* of the vortex, may be due (though this is not well established) to the *nutation* or oscillatory motion of the axis of the hurricane, a phenomenon always existing in every hurricane, but in most of the cases so slight as to escape detection. In fact, when the nutation is small, the axis then being nearly perpendicular to the track, all the sections of the whirlwind will be about horizontal (disregarding the spiral shape of the storm), and, in consequence of this, the ascending air will produce the phenomena referred to. But when the nutation, owing to causes which will be explained farther on, is greater than usual, then the greater will be the obliquity of all the sections of the whirlwind, and in this way the precipitation will be more abundant toward the place opposite to the inclination of the axis.

The nutation of the axes in the tropical hurricanes was discovered by Father Viñes in September, 1876. The hurricane of October 19 of the same year had a greater inclination in its axis than that of September. Contrary to the usual process, the hurricane of October had the mildest winds in the so-called dangerous semicircle, or right side of the storm. In the passage of this hurricane through the island the fact could be well established that the winds on the right side ran at a great altitude, damaging only the royal palms and other tall trees, while sugar cane, tobacco, and other shrubs remained intact. On the contrary, on the left side nothing escaped the fury of the storm, the gusts there being generally like small whirlwinds of terribly destructive violence.

Consequent upon the great nutation of the axis in this hurricane, at least as far as the first part of its track was concerned, the precipitation was highly irregular around the vortex.

A careful examination of delineated tracks of tropical hurricanes will always show the nutation of their axes. The shape of the tracks is that of an undulating curve.

We regard the nutation of the axes in tropical hurricanes as a new and strong argument favoring the theory that tropical hurricanes are directed or impelled in their tracks by the upper atmospheric current. In fact, however regular and steady the current may appear in its course (owing to the defective means of observation of which we can avail ourselves for its study), such regularity and steadiness are more apparent than real. It is hardly conceivable that an atmospheric current (and especially during the months of cyclonic activity, when the atmosphere is so turbulent), may be not subjected to continuous and rather rapid changes in intensity, and, as the hurricanes run along with it, they can not escape its disturbing influence; and hence the nutation of the axes and the irregularities ever existing in their progressive motions.

Position of the observer in relation to the track, and how to ascertain it by observations of the bar.—The attentive observation of the *bar*, will always furnish the observer with the following interesting results:

1. If after a series of observations, embracing six hours as a minimum, he finds that the *bar* has been moving to his *right* (supposing the observer is facing the bar), he is on the right side of the track, or dangerous semicircle. The wind, of course, will move to the right also, that is to say, from north to east, south, west, and north.

2. If the movement of the bar and wind takes place with rapidity the vortex will pass not far from the observer. On the contrary, if the changes take place slowly, then either the vortex will pass at some distance from the observer, or the hurricane will be recurving. The latter assumption will be strengthened if the barometer ceases to fall.

3. If, after a series of observations, performed in the above-cited manner, the observer finds that the bar has been moving to his *left*, then he will be on the left side of the track. The wind will also move to the left: from north to west, south, east, and north.

The deductions from the rapidity or slowness of the movement of the bar and wind are the same as recited in paragraph 2.

4. If after a series of observations the observer finds that the bar remains stationary on the horizon, while the barometer descends rapidly, and the wind velocity and showers continually increase, then he will be situated in the same track as the hurricane, and sooner or later will be in the middle of the vortical calm.

Approximation of the vortex; phenomena to be observed in its vicinity, and before its crossing the point from which it is observed.—It has already been stated that the stability of the bar at the same point on the horizon, attended by continuous and rapid falling of the barometer, and progressive increase in the wind velocity and frequency of the showers, was conclusive evidence that the observer was situated in the track of the hurricane.

In this case, as we have had ample opportunity to verify, the bar is slowly growing in altitude, until reaching about 20° on the horizon. Simultaneously with this increase in the bar, the wind velocity increases largely; the absolute maximum velocity of the gusts being generally from 90 to 100 miles an hour, while the mean velocity averages 65 miles per hour. Showers fall unabated, darkness and mist shut out the horizon, and the barometer descends with unusual rapidity. As the vortex approaches, the moment comes when the wind begins to abate, and the showers gradually to relax in copiousness, notwithstanding the still increasing fall of the barometer. It is easy to see then how the bar has been spreading on the horizon, and now looks like an enormous ring, 20° in altitude, inclosing the observer in its center.

The elapsed time from when the wind and showers begin to abate until the vortical calm is settled and the barometer stationary, is highly variable with different hurricanes, being necessarily dependent upon the diameter of the storm itself and the velocity of its translation.

Vortical calm; phenomena to be observed therein.—The abatement in the wind velocity and force of the showers, to which we have referred in the last section, goes on slowly but steadily, so that the transition from the fury of the hurricane to the relative vortical calm is always accomplished in a gradual and progressive manner.

In passing now to examine the so-called vortical calm and the phenomena to be observed therein, we have—

1. That in the tropical hurricanes this calm is only relative, owing, it may be, its name of calm to the notable disparity between the lull and the tumult of a few hours before, which is to be repeated a few hours later. In fact, in

the so-called vortical calm, the wind velocity is seldom less than 6 miles an hour, though it never goes beyond 10 miles. In spite of this, it is often the case that this relative calm is suddenly broken off by an unexpected gust of 25 to 30 miles an hour, and the approximated duration of which is limited to a few seconds.

2. That the gentle winds of the vortical calm are highly variable or unstable in their direction. It is frequently the case that these winds, within a few minutes, shift around the entire compass.

3. That during the vortical calm the zenith is always clear, stars up to the sixth magnitude being easily discernible.

4. That the barometer remains stationary for a time, highly variable in different hurricanes, the minimum reading during any given hurricane being indicated at the period of vortical calm.

5. That the bar of the hurricane, appearing as an enormous ring, incloses the observer in its middle.

6. That the case is frequent when the bar of the hurricane appears as an ellipse of great eccentricity, whose transverse, or major axis, bears variably during different hurricanes. During the passing of the vortex of the hurricane of September 24, 1894, through Havana, the track of this hurricane, and the observed pressure fall, at the Vedado Park Observatory, the bar of the storm had an elliptical shape, whose major axis extended notably from west to east. Consequent upon this elliptical shape of the bar the space of the vortical calm in these cases extends itself more in the direction of the major axes. This phenomenon is ascribed to the nutation of the axes.

Phenomena to be observed after the passage of the vortex through the point of observation.—These phenomena are—

1. Differing from the procedure observed before the passing of the vortex where the wind is gradually abating, until the vortical calm is settled, after the passing of the vortex, the transition from the calm to the new storm winds is generally accomplished in a sudden and violent manner, so that those gentle winds running from 6 to 10 miles an hour are unexpectedly substituted by gusts of 80 and 90 miles per hour. These winds are always terrible, and especially so on the seas, on account of their unexpected arrival.

2. The observer must ever bear in mind that these awful gusts *always blow from a quarter diametrically opposed* (180° departure) *to that from which the last violent gusts were blowing before the relative vortical calm was settled,* and he must disregard the wind direction during the vortical calm, which is highly variable, as we have said in paragraph 2 of the last section.

3. Shortly before the appearance of the new stormy winds (though sometimes simultaneously), the barometer begins to rise rapidly. This rising goes on unabated until the hurricane has fully passed.

4. Soon after the beginning of the new stormy winds the showery precipitation is again resumed. This precipitation is generally less abundant than that in the forepart of the hurricane.

5. Sometimes the winds blowing in the rear of the hurricane are more violent than those in the front. For instance, in the hurricane of September 24, 1894, before the passing of the vortex through Havana, the absolute maximum velocity of the wind was 43 meters per second, or 95.5 miles per hour. On the contrary, shortly after the vortical calm was over, the absolute maximum velocity recorded in our anemo-cinemographe was 50 meters per second, or 111 miles per hour. In this hurricane, owing to the nutation, the axis of the storm was remarkably inclined from west to east.

6. In the progressive recession of the vortex all the phenomena previously described as taking place during its approaching, come again to sight, with only the difference of being now in a quite reverse order of succession.

Velocities of translation at different points of the track.—1. From the time the hurricane is formed until it reaches the vicinity of the vortex of its parabola, or recurving point, the velocity of translation increases moderately, the average (derived from the observation of many cases) being 15 miles an hour.

2. On the vortex of the parabola, or recurving point, the velocity of translation only averages 6 miles per hour. Sometimes this velocity is limited to 1½ mile per hour.

3. Shortly after recurving, the velocity of translation increases anew, reaching on an average a maximum of 35 miles an hour.

The foregoing review or summary of writings regarding the law of storms, as it applies to West Indian hurricanes, will be concluded with a discussion of the Features of Hurricanes, by Prof. F. H. Bigelow, of the Weather Bureau, in the Yearbook of the Department of Agriculture for 1898:

Hurricanes occur in the southeastern parts of the United States and adjacent waters during the season of the year when the cooling of the Northern Hemisphere takes place as the sun retreats toward the Southern Hemisphere. At this season the calm belt of the Tropics and the heated, moist condition of the air in the region known as the doldrums are at their farthest northern limit. The South Atlantic permanent anticyclone, which lies over the subtropical ocean, is in its fullest vigor. Now, superposed upon these states of the lower atmosphere, the colder temperatures of the upper atmosphere, caused by the approaching autumn, on account of the more rapid circulation higher up, overspread the tropic strata near the surface. As the polar air cools first, it flows gradually above the warmer air at the south of it near the ground, and covers it with a circulating sheet of temperature cool or low for the time of year. The effect of all this is to make the atmosphere unstable, that is to say, too warm at the bottom, compared with that above it, to be able to maintain the usual equilibrium. The tendency is, therefore, for the lower air to rise vigorously and burst its way upward by convection, in order that the normal equilibrium may be restored. Of course, this action is favorable to the formation of cyclonic gyrations and the development of severe storms. Hurricanes seem to generate in some such way as this, though our observations are as yet inconclusive on that point, since there is always observed to be a stagnant, warm condition over the ocean at the time the incipient cyclonic action begins. It is to be especially considered that the isotherms in hurricanes do not show any very decided differences in temperature on opposite sides of the center, such as always prevail in the cyclones of the north. There are no counter-flowing currents here, and no source is known from which these can arise in the equatorial region to produce the marked temperature gradients found in cyclones. Furthermore, hurricanes are much more circular in shape and conform more exactly to the pure theory of cyclones as derived from mathematical analysis.

There is another feature of great interest to be considered. It was stated that in the case of common cyclones, even those having very great strength, the deflection or distortion of the eastward drift at the 3-mile level is only moderate. In the case of hurricanes, which are centered in the east Gulf States, so that the wind directions can be observed on all sides, it is proven that the circulation is not only more rounded, but also that it penetrates the upper strata very much farther, and twists even the cirrus level entirely out of its ordinary shape. The circular components are, therefore, very strong up to 6 miles in hurricanes, while they are equally pronounced in the cyclones only to a height of 3 miles. This is a very marked characteristic, and indicates that hurricanes depend largely upon vertical convection for their power, while cyclones depend almost exclusively upon horizontal convection, that is, upon the counterflow of very long branches of horizontally moving atmosphere, having their bases several thousand miles apart. As hurricanes move northward, out of the Tropics, they gradually assume the nature of true cyclones, since vertical convection is finally superseded by horizontal convection in the North Atlantic districts.

The physical features of hurricanes are well understood. The approach of a hurricane is usually indicated by a long swell on the ocean, propagated to great distances and forewarning the observer by two or three days. A faint rise in the barometer occurs before the gradual fall, which becomes very pronounced at the center; fine wisps of cirrus clouds are first seen, which surround the center to a distance of 200 miles; the air is calm and sultry, but this is gradually supplanted by a gentle breeze, and later the wind increases to a gale, the clouds become matted, the sea rough, rain falls, and the winds are gusty and dangerous as the vortex core comes on. Here is the indescribable tempest, dealing destruction, impressing the imagination with its wild exhibition of the forces of nature, the flashes of lightning, the torrents of rain, the cooler air, all the elements in an uproar, which indicate the close approach of the center. In the midst of this turmoil there is a sudden pause, the winds almost cease, the sky clears, the waves, however, rage in great turbulence. This is the eye of the storm, the core of the vortex, and it is, perhaps, 20 miles in diameter, or one-thirtieth of the whole hurricane. The respite is brief and is soon followed by the abrupt renewal of the violent wind and rain, but now coming from the opposite direction, and the storm passes off with the several features following each other in the reverse order.

By the laws of vortex motion the winds approach the center in spirals, the circular and the centrifugal movements increasing every moment. At the core within the walls of the columnar vortex the air circulates about the calm central part, gradually rising to the cloud stratum, just above the inflowing disk. Here the air flows out suddenly on all sides, the circular motion decreasing, the air cooling by expansion, causing a great, thin sheet of rain 200 to 300 miles from the center. At this distance the vortex sheet turns up suddenly (not down as usually stated) and discharges the expended matter into the high upper currents of the atmosphere. The feeding wind lines are more nearly parallel to the ground than the upper discharge lines, but they all form a columnar vortex of unusual configuration. There is probably no feature of nature more interesting to study than a hurricane, though the feelings of the observer may sometimes be diverted by thoughts of personal safety.

The discoveries and researches reviewed herein cover all available knowledge which is necessary to a practical understanding of West Indian hurricanes.

It will be observed that at the beginning of the three-quarters of a century period, during which these researches have been made, the world possessed no knowledge of the mechanism of storms, and the history of West Indian hurricanes prior to the second quarter of the century is made up solely of local descriptions of their visitations. Toward the middle of the century the paths of hurricanes were successfully traced over the West Indies and adjacent waters and along the Gulf and Atlantic coasts of the United States. During the last quarter of the century hurricanes have been not only accurately traced, but their paths and character have been forecast for the benefit of land and maritime interests which are affected by this class of storms.

The following table, which is taken from Table de Quatre Cents Cyclones by Andreas Poëy, covers the occurrence of three hundred and fifty-five hurricanes which visited the West Indies from 1493 to 1855.

Hurricanes in the West Indies from 1493 to 1855.

Dates.	Localities.
1493, Feb. 12	North Atlantic.
1494, May 19-21	Cuba (between Cape Cruez and Manzanillo).
1494, June 16	Santo Domingo.
1495	Santo Domingo.
1496, Mar.	Atlantic.
1498	Cuba.
1500, Aug	Caribbee Islands.
1502, July 1-2	Santo Domingo.
1502, Dec. 5	Porto Bello; Santo Domingo.
1501, Oct. 19	Atlantic.
1508, Aug. 5	Santo Domingo.
1509, Feb. or Mar.	Gulf of Mexico.
1509, July 29	Santo Domingo.
1510, July	Santo Domingo.
1526, Oct	Santo Domingo.
1527	Cuba.
1530	Porto Rico; Cuba.
1548	Santo Domingo.
1557	Cuba.
1565	Caribbee Islands.
1588	Cuba.
1591, Aug. 10	Latitude 35° north.
1625, Sept. 19	St. Christopher.
1642	Windward Islands; Martinique.
1642	Martinique.
1642	St. Christopher; Martinique; Guadeloupe.
1650	St. Christopher.
1651	Martinique.
1652	Martinique; Guadeloupe; St. Christopher.
1655, July 13	St. Vincent.
1655, Oct. 1	St. Vincent.
1656	Guadeloupe.
1656	Antilles.
1657	Guadeloupe.
1658	Antilles.
1660	Antilles.
1664, Oct. 22, 23	Guadeloupe; Antigua.
1665, Oct	Caribbee Islands.
1666, Aug. 4, 5	Guadeloupe; Martinique; St. Christopher.
1667, Aug. 19	Barbados; Nevis.
1667, Sept. 1	St. Christopher.
1670, Aug. 18	Ninety leagues off Barbados.
1670, Oct. 7	Jamaica; Barbados.
1674, Aug. 10	Barbados; Jamaica.
1675, Aug. 31	Barbados.
1680, Aug. 14	Santo Domingo.
1681	Antigua.
1688, Mar. 1	East of Jamaica.
1691	Antilles.
1692, June 7	Jamaica.
1692, Oct. 24	Cuba.
1694, Aug. 13	Fort James; Barbados.
1694, Oct 17	Barbados.
1695, Oct. 2	Martinique.
1700	Barbados.
1701, April 3	Antilles.
1702	Barbados.
1705, Feb. 7	Antilles.
1707	Nevis; Antigua.
1712, Aug, 28	Jamaica.
1712, Oct	Cuba.
1713	Guadeloupe; St. Thomas.
1714, Aug. 13, 14	Guadeloupe.
1714, Aug. 29	Jamaica.
1714	Cuba.
1718, Mar. 6-7	St. Vincent.
1718, Sept	Nevis.
1720	Barbados.
1722, Aug. 28	Jamaica; Carolina, U. S.
1722, Aug. 31	Antilles.
1725	Martinique.
1726, Oct. 22	Jamaica.
1728, Aug. 19	Antigua.
1728	Carolina, U. S.
1730	Cuba.
1731	Barbados.
1733, June	St. Kitts.
1733, July 16	Cuba.
1734, Sept. 1	Jamaica.
1737, Sept. 9	Santo Domingo; St. Kitts; Montserrat.
1738	Guadeloupe; St. Thomas.
1739, Sept. 9	Antilles.
1740, Aug	Antigua; Martinique; Dominica.
1740	Porto Rico.
1742	St. Thomas.
1744, Oct. 20	Jamaica.
1744, Nov	Cuba.
1745	Caribbee Islands.
1746, Jan	Latitude 40° N.
1747, Sept. 21	St. Christopher; Leeward Islands.
1747, Oct. 24	St. Christopher; Leeward Islands.
1751, Mar. 7	Jamaica.
1751, Aug. 10	Jamaica.
1751, Sept. 2	Jamaica.
1751, Sept. 15	Santo Domingo.
1751, Oct	Jamaica; Dominica.
1752, Sept	Charleston, U. S.
1753, Sept. 15	Charleston, U. S.
1754, Sept	Santo Domingo.
1756, Aug. 25	Barbados.
1756, Sept. 12	Martinique.
1757	From Florida to Boston, U. S.
1757, Aug. 29	Barbados.
1758, Aug. 25	Barbados; South Carolina, U. S.
1759, Sept	Gulf of Mexico.
1761, May 4	Charleston, U. S.
1761, June 1	Charleston, U. S.
1762, Dec. 31	Martinique; St. Eustatius; Guadeloupe.
1765, Sept	Martinique; Guadeloupe, St. Christopher.
1765, Nov. 13, 14	Santo Domingo.
1766, Aug. 13	Martinique.
1766, Aug. 16	West of Jamaica.
1766, Sept. 11	Virginia, U. S.
1766, Sept. 13-15	St. Christopher; Montserrat.
1766, Sept. 21	St. Eustatius; Tortugas.
1766, Oct. 6	Dominica; St. Eustatius; Guadeloupe.
1766, Oct. 22	Pensacola, U. S.
1768, Aug. 12	Grenada.
1768, Oct. 15	Cuba.
1768, Oct. 25	Havana, Cuba.
1769, Aug. 30	West of Florida,
1769, Oct. 29	East of Florida.
1770, June 6	Charleston, U. S.
1771, Aug. 4	Santo Domingo.
1772, Aug. 4	Santo Domingo.
1772, Aug. 16	Santiago, Cuba.
1772, Aug. 17	Antigua.
1772, Aug. 28	Porto Rico; Jamaica.
1772, Aug. 31	Leeward Islands; Virgin Islands; Antigua.
1772, Sept. 1, 4	Dominica; Santo Domingo.
1772, Nov. 22	St. Christopher; St. Eustatius.
1773, July	St. Thomas; Cuba.
1773, Aug	Boston.
1774, Oct. 2	Jamaica.
1775, July 30	St. Croix; Martinique.
1775, Aug. 25	Martinique.
1775, Aug. 27	Santo Domingo.
1775, Sept. 14	Cuba; Santo Domingo.
1775, Oct. 16	St. Christopher.
1776, Sept. 4	Antigua; Martinique; Guadeloupe.
1776, Sept. 5, 6	Martinique; Guadeloupe; St. Kitts.
1778, Oct. 28	Cuba.
1779	New Orleans, U. S.
1780, Aug. 25	St. Kitts; New Orleans.
1780, Oct. 3-12	Jamaica; Cuba; Martinique; Barbados.
1780, Oct. 10-18	Barbados; Dominica; Antigua; Tobago; Grenada; St. Vincent; Santo Domingo.
1780, Oct. 16	Cuba.
1780, Oct. 31	Barbados.
1781, Mar. 15	West Indies.
1781, Aug. 1	Jamaica.
1781, Aug. 10	North Carolina, U. S.
1781, Sept. 5	Santo Domingo.
1782, Apr. 12	North Atlantic.
1782, July 25	Latitude N. 45° 33′, longitude W. 4° 40′.
1782, July 31	Kingston, Jamaica.
1782, Aug. 1	Jamaica.
1782, Sept. 16	North Atlantic.
1784, Mar. 8	Cuba.
1784, July 10	Jamaica.
1784, July 30	Jamaica; Santo Domingo.
1785, July 6	West Indies.
1785, July 25	St. Croix.
1785, Aug. 25	Guadeloupe.
1785, Aug. 27	Jamaica.
1785, Aug. 31	Guadeloupe; Barbados; Santo Domingo.
1785, Sept. 22-24	Carolina and Virginia, U. S.
1785, Sept. 27	Santo Domingo.
1786, Aug. 11	Santo Domingo; St. Eustatius; Barbados.
1786, Aug. 29	United States.
1786, Sept. 2	Barbados.
1786, Sept. 10	Guadeloupe.
1786, Oct. 5	Barbados; Grenada.
1786, Oct. 20	Jamaica.
1787, Apr.	United States; Bermudas.
1787, July 30	United States.
1787, July	Guadeloupe; French Islands.
1787, Aug. 5	Dominica.
1787, Aug. 15	Florida.
1787, Aug. 25	Dominica.
1787, Aug. 29	Dominica.
1787, Sept. 2	Honduras.

Hurricanes in the West Indies from 1493 to 1855—Continued.

Date.	Localities.
1787, Sept. 19	United States.
1787, Sept. 25	Belize.
1787, Dec. 1	West Indies.
1788, Jan	Honduras.
1788, Mar. and Apr	St. Croix.
1788, July 22	United States.
1788, Aug. 14	Martinique.
1788, Aug. 16	Porto Rico; Santo Domingo.
1788, Aug. 19	United States.
1788, Aug. 29	Dominica.
1788, Sept. 19–20	United States.
1790, Aug	Nevis.
1790, July 31	Jamaica.
1791, June 21	Cuba.
1791, Sept. 27	Cuba.
1792, July 15	West Indies.
1792, Aug. 1	Antigua.
1792, Aug. 6	Bermudas.
1792, Sept. 10	Antigua.
1792, Oct. 29	Cuba.
1793, Aug. 12	St. Christopher; St. Eustatius; St. Thomas.
1794, Aug. 27–28	Cuba.
1795, Aug. 10	Jamaica.
1795, Aug. 18	Antigua.
1796, Oct. 5	Bahamas.
1796, Oct. 24	Cuba.
1796, Nov. 2	Cuba.
1799	Cuba.
1800, Nov. 2	Cuba.
1801, July 22	Nassau.
1802, Feb. 21, 25	Charleston; Nova Scotia.
1802, Sept. 16	Cumana.
1803, July 10	Bahamas.
1803, Sept. 3–9	Martinique; Caribbee Islands; United States.
1804, Aug. 29	Jamaica.
1804, Sept. 3–6	Leeward Islands.
1804, Sept. 22	Jamaica; latitude N. 20° 18′
1804, Oct. 4	Savannah, Ga.
1804, Oct. 9	United States.
1805, July 27	Jamaica.
1805, July 29	Latitude 26° 17′, longitude 60° 2′, north of Barbados.
1806, Aug. 30	Bahamas; Eleuthera.
1806, Sept. 9	Dominica.
1806, Sept. 24	Dominica.
1805, Sept. 27	West Indies.
1806, Oct. 5	Bahamas.
1806, Oct. 27	Bahamas.
1807, July 25–28	St. Christopher; Montserrat.
1807, Sept. 5	Cuba.
1809, July 27	Dominica; Guadeloupe.
1809, Aug. 1–5	Dominica; Guadeloupe.
1809, Sept. 2	Guadeloupe; Porto Rico.
1809, Oct. 15	Martinique.
1809, Oct. 18	Trinidad.
1810, Aug. 12	Trinidad; Barbados.
1810, Aug. 28	Barbados.
1810, Sept. 28	Cuba.
1810, Oct. 25, 26	Cuba.
1812, Aug. 14	Jamaica.
1812, Aug. 19	New Orleans, U. S.
1812, Oct. 12	Jamaica.
1812, Oct. 14	Jamaica.
1812, Oct. 14	Trinidad; Cuba.
1815, July 20	Bermudas.
1815, July 22	Barbados.
1815, July 22, 25	Dominica; Martinique; St. Christopher.
1815, July 26	Bermudas; Bahamas.
1815, July 31	Jamaica.
1815, Aug. 1	Jamaica.
1815, Aug. 5–9	North Atlantic.
1815, Aug. 25	Dominica.
1815, Nov. 19	Nova Scotia.
1815	Belize.
1815, Aug. 9	Gulf Stream, latitude 40°, longitude 62°.
1815, Aug. 31, Sept. 1	North Atlantic, latitude 39°, longitude 58°; Bartholomew.
1815, Sept. 20	Turks Island.
1815, Sept. 29	Barbados.
1815, Oct. 18	Jamaica.
1816, Sept. 15	Barbados; Martinique; Dominica.
1816, Oct. 16	Dominica; Martinique.
1817, Sept. 15	Dominica.
1817, Oct. 21	Little Islands; St. Vincent.
1817, Oct. 25	Barbados; St. Lucia; Martinique.
1818, Aug. 28	Bermudas.
1818, Sept. 10, 12	Cayman Islands; Campeche.
1818, Sept. 10	Santo Domingo.
1818, Sept. 22-25	Antigua.
1818, Sept. 27–30	Barbados.
1818, Oct. 7	Port Royal (Jamaica).
1818, Oct. 21	St. Lucia.
1818, Nov. 17, 20	Jamaica.
1819, Aug. 25	Dominica.
1819, Sept. 21–22	St. Lucia; Barbados; Virgin Islands; Porto Rico.
1819, Oct. 13, 15	Barbados; St. Lucia.
1819, Oct. 28	Cuba.
1821, Sept. 1	Guadeloupe.
1821, Sept. 1	Turks Island; Long Island, U. S.
1821, Sept. 9	Antigua; St. Bartholomew.
1821, Sept. 25	New Haven, U. S.
1821	Cuba.
1822, Mar. 11	Jamaica.
1822, July 11	Mobile, U. S.
1822, Dec. 18	Barbados.
1824, July 26	West Indies.
1824, Sept. 7, 8	Guadeloupe.
1825, July 25, 26	Dominica; Martinique; Guadeloupe.
1825, Oct. 1	Cuba.
1826, Aug. 18	Antilles.
1826, Nov. 6–9	Atlantic; Teneriffe.
1826	Cuba.
1827, July 30	North Carolina, U. S.
1827, Aug. 17–28	Windward Islands.
1827, Aug. 28	St. Thomas; Virgin Islands.
1827, Sept. 7	North Atlantic.
1827, Oct. 11	Bahamas.
1827	Belize.
1828, Mar. 15	Gulf of Mexico.
1828, Sept. 19	North Atlantic, northwest of Bermudas.
1829, July 24	Boston, U. S.
1830, Apr. 24, 25	Vera Cruz.
1830, Aug. 7	Jamaica.
1830, Aug. 11–18	Dominica; St. Thomas; Barbados.
1830, Aug. 19-24	Martinique; United States.
1830, Aug. 22-26	Turks Island; north of Bahamas.
1830, Sept. 29	Caribbee Islands, north coast.
1830, Dec. 5, 6	Coast of America, latitude N. 50°.
1831, Apr. 27	United States.
1831	Belize.
1831, Jan. 13–15	Florida.
1831, June 10	Florida.
1831, June 25–27	Trinidad; Tobago; Antigua; Grenada.
1831, Aug. 10-17	Barbados.
1832, June 3–6	Cuba; Bahamas; Bermudas.
1832, Aug. 7	Jamaica.
1833, Aug. 14	Guadeloupe; Antigua; Bermudas.
1833, Sept. 20	Dominica.
1833, Oct. 16–19	Cuba; Gulf of Mexico.
1834, Sept. 20	Dominica.
1834, Oct. 20, 21	Martinique.
1835, April 28	Coast of the United States.
1835, July 26	Barbados.
1835, Aug. 12–18	Antigua; Cuba; Galveston.
1835, Sept. 5	Barbados.
1835, Sept. 18	Matamoras; Gulf of Mexico.
1835, Nov. 10	Nova Scotia.
1836, Nov. 30 and Dec. 21	United States.
1837, July 9	Barbados; St. Lucia.
1837, July 26	Barbados; Cuba; Martinique.
1837, July 31	Antigua; St. Thomas.
1837, Aug. 2–4	Antigua; St. Thomas; Barbados.
1837, Aug. 6	Lesser Antilles.
1837, Aug. 12	Northeast of Caribbee Islands.
1837, Aug. 18–21	Latitude N. 32° 45′, longitude E. 79° 47′.
1837, Aug. 12–23	Turks Island.
1837, Aug. 31	St. Mark.
1837, Aug. 31 to Sept. 3	Apalachicola, U. S.
1837, Sept. 27 to Oct. 10	Gulf of Mexico.
1837, Oct. 1–5	Yucatan Channel, in the Gulf of Mexico.
1837, Oct. 26	Cuba.
1838, Sept. 10	Bahamas.
1838, Nov. 1	Vera Cruz.
1838, Nov. 26	Vera Cruz.
1838, Nov. 26–28	Atlantic coast of Europe.
1839, June 9	Antigua.
1839, Sept. 8–14	Bermudas.
1839, Nov. 5	Galveston, near Island of St. Louis, Gulf of Mexico.
1839, Dec. 15–17	United States; North Atlantic.
1840, May 25	Madeira.
1840, Sept. 16	Porto Rico.
1841, Oct. 3–6	Nantucket, U. S.
1841, Oct. 6	Barbados; St. Lucia.
1841, Oct. 21–28	Bermudas.
1841, Nov. 28	Cuba.
1842, July 12	Cape Hatteras, U. S.
1842, Aug. 30 to Sept. 2	Atlantic and the coasts of Mexico.
1842, Sept. 4	Cuba.
1842, Oct. 2–10	Bermudas.
1842, Oct. 24–29	Madeire,

Hurricanes in the West Indies from 1493 to 1855– Continued.

Dates.	Localities.
1842, Nov. 5	Latitude 56° 40′, longitude 65° 20′.
1843, Oct. 13	Florida.
1844, Feb. 22	Martinique.
1844, May 12	Latitude N. 37° 47′, longitude W. 67° 42′.
1844, Oct. 5	Cuba.
1845, Oct. 12	Straits of Florida.
1845, Oct. 22	Bermudas.
1845, Oct. 27	Bermudas, east coast.
1845, Nov. 9	Bermudas.
1846, Sept. 11–21	Barbados; Guadeloupe; Antigua.
1846, Oct. 6–18	Cuba; United States.
1847, Feb. 21	Atlantic.
1847, Oct. 10	Tobago; Trinidad.
1848, Aug. 22 to Sept. 3	Antigua.
1848, Sept. 19	Barbados; St. Christopher.
1848, Dec. 16	Atlantic.
1849, Mar. 27	Latitude N. 48°, longitude W. 22°.
1850, Mar. 30	Nassau.
1850, July 14–16	Islands of the south and west.
1850, Aug. 21	Cuba.
1850, Sept. 2	St. Nicholas; Cape Verde Islands.
1850, Oct. 14	Latitude 24° 59′, longitude 49° 50′.
1850, Oct. 18	Latitude 25° 58′ N., longitude 43° 39′ W.
1851, Aug. 16–28	St. Mark; Florida; St. Christopher; St. Thomas; Cuba.
1851, July 10	Barbados; Santo Domingo; St. Christopher.
1852, Jan. 12	Vera Cruz.
1852, Sept. 22–26	St. Christopher; St. Eustatius; Porto Rico.
1852, Oct. 9	St. Mark; Florida.
1853, Aug. 30	Cape Verde.
1853, Sept. 11	Hatteras, U. S.
1853, Sept. 27	Latitude 35° 19′, longitude 58° 56′.
1853, Sept. 28	Latitude N. 15°, longitude 37° 10′.
1854, Oct. 21	Bermudas.
1855, Jan. 20	Baltimore, U. S.; Halifax,
1855, Feb. 10	Bermudas.
1855, May 24	Trelawny.
1855, Aug. 25–26	Martinique; Santo Domingo.

The distribution of these hurricanes during the different months was as follows:

Month.	No. of hurricanes.
January	5
February	7
March	11
April	6
May	5
June	10
July	42
August	96
September	80
October	69
November	17
December	7
Total	355

From 1856 to 1877 the occurrence of twelve hurricanes was noted by various writers, and the storms of that period complete an inexact record of hurricanes for nearly four hundred years.

From 1878 to 1900, inclusive, observations and data collected by the United States Weather Bureau permitted accurate tracings and descriptions of hurricanes that occurred over the Caribbean Sea, the West Indies, and adjacent waters, and the hurricanes thus described and traced will be made a base for determining facts regarding the movement and characteristics of storms of this class.

Movement of West Indian Hurricanes, 1878 to 1900, Weather Bureau records.

Date.	Latitude north.	Longitude west.	Appeared.	Latitude north.	Longitude west.	Recurved.	Disappeared.
May, 1889	22	65	North of Lesser Antilles	30	75	Off south Atlantic coast	Off south New England coast.
June, 1886	24	87	Off western Cuba	25	87	Gulf of Mexico	Middle Atlantic coast.
June, 1886	17	80	Caribbean Sea	25	89	Gulf of Mexico	Off middle Atlantic coast.
June, 1889	20	85	Caribbean Sea	23	86	West of Cuba	Off New England coast.
July, 1886	19	83	Caribbean Sea	25	88	Gulf of Mexico	Mid Atlantic Ocean.
July, 1886	25	85	Gulf of Mexico	25	87	Gulf of Mexico	Mid Atlantic Ocean.
July, 1887	14	61	Windward Islands	21	89	Yucatan	East Gulf States.
Mean	20	80		24	88		
August, 1878	15	78	Caribbean Sea			No recurve	West Gulf.
August, 1879	16	65	Caribbean Sea	20	78	Cuba	South of Newfoundland.
August, 1879	20	90	Yucatan	25	95	Gulf of Mexico	South of Newfoundland.
August, 1880	15	80	Caribbean Sea			No recurve	Texas.
August, 1880	27	69	East of Bahamas			No recurve	East Gulf States.
August, 1880	18	58	East of Windward Islands	21	79	Cuba	Northeast of Bahamas.
August, 1880	26	61	Southeast of Bermudas	32	65	Near Bermudas	North of Bermudas.
August, 1881	20	63	North of Windward Islands			No recurve	Mississippi Valley.
August, 1883	22	58	Northeast of Windward Islands	33	70	West of Bermudas	Northwest of British Islands.
August, 1883	28	68	North of Windward Islands	34	70	West of Bermudas	Mid ocean.
August, 1886	11	59	East of Windward Islands			No recurve	Gulf of Mexico.
August, 1886	26	92	Gulf of Mexico			No recurve	Southeastern slope of Rocky Mts.
August, 1886	12	59	East of Windward Islands	22	80	Cuba	South of Iceland.
August, 1887	21	67	North of Porto Rico	28	79	North of Bahamas	North Sea.
August, 1887	17	58	East of Windward Islands	27	79	North of Bahamas	Mid ocean.
August, 1887	17	72	Caribbean Sea			No recurve	South of Cuba.
August, 1888	25	79		30	93		East of Newfoundland.
August, 1890	18	57		30	70		South of Nova Scotia.
August, 1891	14	59				No recurve	West Gulf of Mexico.
August, 1892	20	65		25	70		Northeast of Newfoundland.
August, 1893	22	57		27	77		Northeast of Newfoundland.

Movement of West Indian Hurricanes, 1878 to 1900, Weather Bureau records—Continued.

Date.	Latitude north.	Longitude west.	Appeared.	Latitude north.	Longitude west.	Recurved.	Disappeared.
August, 1893	21	61		28	75		North of Newfoundland.
August, 1893	15	66		30	75		Northeast of Newfoundland.
August, 1895	15	70				No recurve	Rio Grande Valley.
August, 1899	16	60		27	80		South of Nova Scotia.
Mean	19	67		27	77		
September, 1878	11	60	East of Windward Islands	24	81	Florida	South of Iceland.
September, 1878	15	71	Caribbean Sea	19	73	North of Haiti	Northeast of Bahamas.
September, 1878	14	49	East of Windward Islands	25	60	North of Windward Islands	North Sea.
September, 1879	15	68	Caribbean Sea	23	87	Gulf of Mexico	Mid ocean.
September, 1881	25	70	North of Haiti	33	76	North Carolina coast	New England coast.
September, 1882	21	72	North of Haiti	25	88	Gulf of Mexico	Near Iceland.
September, 1883	15	66	Caribbean Sea	30	79	South Atlantic coast	South of lower Lakes.
September, 1884	14	47	East of Windward Islands	20	58	Northeast of Windward Islands.	Northeast of Windward Islands.
September, 1885	27	56	Northeast of Windward Islands.			No recurve	South of Nova Scotia.
September, 1885	24	89	North of Yucatan	25	93	Gulf of Mexico	Mid ocean.
September, 1885	23	97	West Gulf	23	97	West Gulf	Northwest of British Islands.
September, 1886	22	66	North of Porto Rico			No recurve	West of Bermudas.
September, 1886	14	62	Windward Islands	22	97	Gulf of Mexico	Middle Mississippi Valley.
September, 1887	13	57	East of Windward Islands			No recurve	Northern Mexico.
September, 1888	20	65				No recurve	Central America.
September, 1889	14	57		22	67		North Carolina coast.
September, 1889	14	69		25	92		New England.
September, 1894	16	60		23	82		Southeast of New England.
September, 1896	23	85				No recurve	North of St. Lawrence Valley.
September, 1897	25	83				No recurve	Texas.
September, 1897	22	85				No recurve	Newfoundland.
September, 1898	13	57		25	74		Bermudas.
September, 1899	15	64		21	74		Mid ocean.
September, 1899	17	61		25	67		Mid ocean.
September, 1900	13	63		24	95		Mid ocean.
Mean	18	67		24	80		
October, 1878	25	50	Northeast of Windward Islands.	32	52	Northeast of Windward Islands.	Mid ocean.
October, 1878	17	41	Northeast of Windward Islands.	18	55	Northeast of Windward Islands.	East of Bermudas.
October, 1878	25	72	East of Bahamas	25	73	Northeast of Bahamas	North of Europe.
October, 1878	17	81	Caribbean Sea	21	81	Cuba	South of Newfoundland.
October, 1879	16	71	Caribbean Sea	33	89	Mississippi Valley	Lake region.
October, 1880	25	61	North of Windward Islands	30	63	Southeast of Bermudas	Northeast of Bermudas.
October, 1881	25	60	North of Windward Islands	30	63	Southeast of Bermudas	Southern Europe.
October, 1882	20	83	Caribbean Sea	23	83	Cuba	Near Iceland.
October, 1883	30	65	South of Bermudas			No recurve	South Atlantic coast.
October, 1883	27	79	Bahamas	27	79	Bahamas	South of Iceland.
October, 1884	22	72	North of western Cuba	24	76	Bahamas	South of Newfoundland.
October, 1886	21	84	Caribbean Sea	30	95	West Gulf States	Middle Mississippi Valley.
October, 1886	17	70	Caribbean Sea	19	70	Santo Domingo	East of Newfoundland.
October, 1887	19	44	East of Windward Islands	20	58	Northeast of Windward Islands.	Mid ocean.
October, 1887	17	52	East of Windward Islands	25	56	Northeast of Windward Islands.	South of Newfoundland.
October, 1887	18	80	Caribbean Sea			No recurve	Gulf of Mexico.
October, 1887	15	78	Caribbean Sea	24	97	West Gulf	Northeast of Iceland.
October, 1889	15	61		28	68		Southeast of Newfoundland.
October, 1891	23	58		35	70		Northeast of Newfoundland.
October, 1891	16	63		18	70		Newfoundland.
October, 1891	20	83		21	83		Northeast of Newfoundland.
October, 1892	25	91		28	91		Newfoundland.
October, 1893	21	54		27	79		North of Newfoundland.
October, 1894	23	63		25	75		East of Newfoundland.
October, 1894	12	64		25	67		East of Newfoundland.
October, 1894	14	78		24	88		North of Newfoundland.
October, 1895	16	80		23	80		Bermudas.
October, 1895	23	83				No recurve	East of Newfoundland.
October, 1897	22	83		23	85		Off New England coast.
October, 1898	20	70		35	86		Newfoundland.
October, 1899	21	82		26	84		Newfoundland.
October, 1899	19	78		22	81		Newfoundland.
Mean	20	70		26	76		
November, 1878	13	51	East of Windward Islands			No recurve	Caribbean Sea.
November, 1879	15	68	Caribbean Sea	24	78		Mid ocean.
November, 1888	22	57		24	78		South of Newfoundland.
Mean	17	59		24	78		
December, 1885	15	76	Caribbean Sea	18	77	Jamaica	East of Iceland.
December, 1887	19	54	Northeast of Windward Islands.	33	62	East of Bermudas	South of Iceland.
December, 1887	25	62	North of Windward Islands	29	65	South of Bermudas	East of Bermudas.
Mean	20	64		27	68		

The following table shows, by months, the number of West Indian hurricanes that appeared, the average position in which they were first located, and the region in which they disappeared during the twenty-three years, 1878 to 1900, inclusive:

Month.	No. of hurricanes.	Appeared.		Recurved.		Disappeared.
		Latitude north.	Longitude west.	Latitude north.	Longitude west.	
May	1	22	65	30	75	Off south New England coast.
June	3	20	84	24	87	2 off middle Atlantic coast; 1 off New England coast.
July	3	19	76	23	88	2 off middle Atlantic coast; 1 over east Gulf States.
August	25	19	67	27	77	9 no recurve; see charted tracks.
September	25	18	67	24	79	6 no recurve; see charted tracks.
October	32	20	70	26	76	3 no recurve; see charted tracks.
November	3	17	59	24	78	See charted tracks.
December	3	20	64	27	68	See charted tracks.

The above table shows that 76 of the 95 West Indian hurricanes traced during the last twenty-three years had a recurve to the northward; that during the principal hurricane months, August to October, inclusive, the hurricanes generally recurved east of the Gulf of Mexico; and that, during these months, the mean track of the hurricanes was farther west in September, when it approached very near the east Florida coast. The figures in the table which summarize the mean courses of the hurricane for the several months can, however, be given but little weight, and a reference to the charted tracks will show that during the principal hurricane months these storms are liable to appear in any part of the region lying between the tenth and twenty-fifth parallels and east of the eightieth meridian, and to recurve from far to the eastward of the Bahamas to the west coast of the Gulf of Mexico. It is apparent, however, that the tracks run farther south and west in September, and hurricane visitations are, therefore, more probable on the Island of Cuba and on the United States coast in September; and this is equally true as regards the frequency of hurricanes on the more eastern islands of the Greater Antilles. The belief, founded upon local experiences, that the hurricane tracks shift farther west as the season advances, is doubtless well grounded; and it is safe to assume as a fact that the more severe storms of the West Indies usually occur over the Lesser Antilles and the eastern islands of the Greater Antilles in the early part of the hurricane season, and over the western parts of the Greater Antilles as the season advances.

The table, which summarizes by months the number of hurricanes which occurred during the 23-year period, 1878 to 1900, inclusive, shows a total of 95 storms, of which number 82, or about 90 per cent, occurred during the months of August, September, and October. The month of greatest hurricane frequency was October, with a total of 32, or about 34 per cent of the entire number. August follows with 25, and September with 25 hurricanes. The greatest number that occurred in any of the remaining months was 3, in June, July, November, and December. But one hurricane is noted for the month of May, and no storms of this class have appeared within the region of observation during the months of January, February, March, and April.

While the foregoing tables and accompanying charts show the individual and mean tracks of West Indian hurricanes it will be profitable to again briefly refer to the conditions and causes which appear to control the movements of these storms. These conditions and causes are outlined in Weather Bureau Bulletin A in part, as follows:

> The recurve of storms in the West Indies and over the Gulf of Mexico is dependent upon general meteorological conditions, and more especially upon the distribution of atmospheric pressure. The anticyclonic or high pressure area of the North Atlantic Ocean lies northeast of the West Indies, and causes east to northeast winds over the southern part of the ocean and the Caribbean Sea. The storms that develop in the region east of the West Indies, and also those of a more western origin, have a tendency to follow the course of the main equatorial current over the Caribbean Sea. This course is doubtless largely influenced by the general drift of the atmosphere in that region, and, following the anticyclonic circulation of winds, the hurricanes skirt the western quadrants of the Atlantic high area, and, carried by the general drift of the atmosphere, follow paths which recurve north and northeastward near the southeastern coasts of the United States. As a majority of the hurricanes traced followed the course indicated, it may be considered the usual course of West Indian storms when the usual meteorological conditions obtain over the southern and southwestern North Atlantic Ocean and the eastern part of the United States. Some of the more important storms that originate near the West Indies do not recurve to the northward but move westward over the Gulf of

Mexico and dissipate over Mexico or the Southwestern States. In such cases high barometric pressure to the northward apparently prevents a recurve.

Observation has shown that storms are commonly more violent in the region where they recurve or attempt to recurve. Observation has also shown that when the advance of a storm is obstructed, and it is forced or held back by an area of high pressure which persistently occupies the region through which the storm would pass with the prevalence of usual conditions, the storm acquires greater intensity before dissipating or assuming an abnormal course. Among notable storms of this class may be mentioned the hurricane of August, 1886, which totally destroyed the City of Indianola, Tex., and the hurricane of September, 1888, which raged with destructive violence over Cuba. These storms were apparently unable to recurve, owing to high barometric pressure to the northward. Forced westward they developed intense energy and dissipated, one on the southeast slope of the Rocky Mountains, and the other over eastern Mexico.

Aside from the fact that they commonly emerge from the region of equatorial rains, which lies between the Lesser Antilles and the African coast, little is known regarding the place of origin of West Indian hurricanes. It has seemed allowable in instances to assume that storms which have been encountered by vessels far to the eastward of the Lesser Antilles have subsequently visited the West Indies, but owing to the very meager amount of data which has been received from the tropical ocean such assumptions are not susceptible of proof. It is not improbable, however, that some of the West Indian hurricanes originate over the mid-Atlantic Tropics and even well over toward the Cape Verde Islands. The latitudinal limits of the region within which these storms originate may be safely represented by the parallels of eight and twenty degrees north, and it is believed that they have their origin along the line of the southern limit of the northeast trades. As the summer advances the North Atlantic area of high barometer settles southward over the eastern Atlantic, forcing the limit of the trade winds southward, and causing hurricanes to form farther and farther to the westward until October, when they develop or originate, over the eastern Caribbean Sea, or but a little distance east of the Lesser Antilles.

The manner of their origin is a matter of speculation and theory. The writer in an article published several years ago in the American Meteorological Journal stated that "Storms are incubated by heat and nourished by moisture." In the region of equatorial rains from whence these storms emerge are found all of the known and recognized elements which contribute to a storm's formation and subsequent intensity. The northeast trade winds strike an almost quiescent mass of exceedingly moist and warm air which possesses an initial upward or rising motion. The striking of the trades into this mass is calculated to cause atmospheric whirls or eddies, and when these whirls become sufficiently pronounced they develop into well-marked cyclonic disturbances, which, under the most favorable conditions, acquire hurricane intensity and are carried westward over the West Indies by the prevailing general wind currents.

The remainder of this paper will be devoted to descriptions of the more important hurricanes that have occurred in the West Indies, over the Atlantic Ocean, and along the North American coasts. A number of these descriptions, from 1873 to 1896, have been collected by Prof. A. J. Henry, of the Weather Bureau, and the record has been continued throughout the year 1899. Following these descriptions reference is made to some of the great and historical hurricanes which occurred prior to 1873.

AUGUST HURRICANES.

1. *Hurricane of August 14–27, 1873.*—The most destructive that ever visited the Atlantic coast, charted in Memorandum of Useful Information for Shipmasters, 1885, as Hurricane No. 1, of August, 1873. First reported by bark *Crest of the Wave* in latitude 14°, longitude 27°, August 13; in latitude 22°, longitude 60° on the 18th, noon; on the 19th, noon, latitude 22°, longitude 63°; 20th, latitude 27°, longitude 66°; 21st, latitude 30°, longitude 65.5°; 22d, latitude 35.5°, longitude 68.5°; 23d, in latitude 37°, longitude 67°; at midnight of the 24–25th the storm believed to have been in latitude 44°, longitude 56°; on 25th, at noon, central in latitude 44.5°, longitude 54.5°; noon of the 26th, latitude 44.5°, longitude, 50°; twenty-four hours later, in latitude 49.5°, longitude 54.5°. Proceeding

in a northwesterly course, it recurved between the islands of Bermuda and Cape Hatteras, taking a northeasterly course, its center at no time touching the coast line. Between sunset and sunrise of the 24th and 25th occurred the greatest destruction in the region of Halifax, Sydney, Charlottetown, and the coast of Nova Scotia, due to a terrific easterly wind, which, within twenty-four hours, backed from southeast to to northwest.

The marine losses from this storm amounted to 1,223 vessels, with 223 human lives. The region of coast which suffered most included Cape Breton, Gaspe, Labrador, Magdalen Island, New Brunswick, Nova Scotia, Newfoundland, and Prince Edward Island, where the damage and destruction affected breakwaters, wharfs, docks, bridges and railways, buildings, particularly churches, and to some extent, growing crops. A total of 897 buildings was reported destroyed, and a total money loss of $698,000 was reported, though in many instances the money losses were not estimated, the damage being stated as "great," "immense," or "incalculable."

2. *Hurricane of August 16–20, 1879.*—A severe Atlantic coast storm, most severe at Cape Lookout, with very high wind and high seas. Charted in Memorandum of Useful Information for Shipmasters, 1885, as Hurricane No. V, August, 1879. Course from about latitude 18.5°, longitude 60°, on 13th. On the 15th, latitude 20°, longitude 69°, north of Haiti; on the morning of the 17th about latitude 25.5°, longitude 76°. Storm center off the South Carolina coast the same date; Wilmington, N. C., on the 18th, then up the coast in a north-northeasterly direction, reaching the region of Nova Scotia on the 19th.

On the 18th the gale commenced at Wilmington, N. C., and at 5 a. m. was blowing west, 68 miles. At the same hour, at Cape Lookout, the wind had increased to southeast, 80 miles, with torrents of rain, and a fearful sea. At 6:30 a. m., at Cape Lookout, the barometer had fallen to 29.15 and the sea was increasing, the wind blowing 138 miles; the anemometer cups were carried away; at 7:30 the wind had reached its greatest velocity, estimated at southwest, 165 miles.

At Portsmouth, N. C., 6:30 a. m., the wind was southeast, 49 miles, and at 8:45 was southeast, 97 miles, when the recording apparatus was temporarily disabled. At Cape Hatteras the wind reached its maximum recorded velocity, southeast, 74 miles, when anemometer cups were blown away. At Kittyhawk, N. C., 9:30 a. m., the wind was southeast, 100 miles; Norfolk, Va., 10:45 a. m., barometer, 29.16, wind northeast, 48 miles; Cape Henry, Va., 11 a. m., wind north, 66 miles, when it moderated, then shifted to northwest, and increased to 70 miles; Atlantic City, N. J., 3 p. m., northeast, 60 miles, and at Barnegat, N. J., 5 p. m., north, 64 miles, with 5.39 inches of rain in nine hours.

In New England heavy rains and east and northeast winds prevailed during the preceding day. The storm commenced at New Haven, Conn., about noon, and had extended from New Bedford, Mass., to Portsmouth, N. H., by 8 p. m. At Easport, Me., 10:30 a. m., on the 19th, the barometer registered 29.20; wind northeast 34 miles. On the afternoon of the 19th the storm passed into New Brunswick.

The amount of damage could not be estimated. Inland property in the track of the storm was damaged extensively, while the marine losses must have been enormous, as 100 large vessels and 200 small craft were wrecked or injured, not a few of the latter being pleasure yachts. Highest wind velocity in New England, as reported, 54 miles at Thatchers Island, Mass., and Eastport, Me. The storm was especially interesting on account of the rapid and extreme fluctuations of pressure, with attending phenomena, near the immediate center.

3. *Hurricane of August 22–26, 1881.*—A destructive hurricane which was very general in extent, striking the coasts of Georgia and South Carolina, and passing inland in a northwesterly direction; it finally crossed Minnesota and entered the British Possessions.

The center of the storm was reported at St. Thomas at 3 a. m., August 23, and at Turks Island, W. I., 3 p. m., on the 24th. The first indications of the storm on the United States coast were noted on the 26th, the greatest violence being manifested on the 27th, in many localities there being no abatement until the morning of the 28th. In the Charleston, S. C., report it was stated to be "the most violent since the great storm of August, 1874," and Savannah, Ga., reported that "the memorable storm of 1854 was not so violent or prolonged." (See close of account of September hurricanes, in this article).

The storm was unusually severe all along the coast line from Georgia to North Carolina, extending as far north as Cape Fear, the sea islands in many instances being submerged with great loss of life, and destruction to property and crops, while all islands in the track of the storm were devastated to a more or less extent.

The damage to property in Savannah, Ga., was estimated at $1,500,000, with a loss of 335 human lives. Lives were also lost at other points along the coast, and cattle, horses, and other stock destroyed. The terrible destruction was due to unusually high winds and high water, and to the long continuance of the winds at hurricane force. The storm was accompanied by torrents of rain. There were a few reports of losses in the interior, particularly at Montgomery, Ala.

On the morning of the 29th the storm center was near Memphis, Tenn., heavy rain having fallen along the path of the cyclone. The next morning the center had moved into Iowa and thence to the northeast.

Five storms during this month are noted in the Jamaica Meteorological Observations, Vol. I, this storm being No. 3 of the Jamaican account.

4. *Hurricane of August 23-24, 1885.*—Another destructive hurricane which particularly affected the coasts of Georgia and the Carolinas, the reports showing that it was also violent at sea, from the 23d to the 26th.

On the 23d the schooner *E. B. Conwell* encountered a hurricane off the Florida reefs. The midnight map of the 24th showed the center of cyclone near Savannah, Ga. At 7 a. m. of the 25th it was near Charleston, S. C., and west of Smithville, N. C. At midnight it was northwest of Wilmington, N. C., and west of Hatteras, N. C., and on the 26th had passed off the North Carolina coast. The winds attending the cyclone were terrible in their force along the south Atlantic coast, and high winds (25 miles) were mentioned at all stations on the coast from Florida to Massachusetts. The following high velocities are noted: Savannah, Ga., 56 miles; Tybee Island, Ga., 75 miles; Smithville, N. C., 98, miles, estimated 125 after anemometer cups were blown away; Hatteras, N. C., maximum velocity of 52 miles.

The greatest destruction occurred at Charleston, S. C., where the damage was estimated at $1,690,000, and the loss of life was placed at 21 persons. At Smithville, N. C., the damage to town and county amounted to $100,000. At Savannah, Ga., it was said to be the most severe storm since August 27, 1881.

5. *Tropical hurricane of August 13-20, 1886.*—The first appearance of this storm was over the eastern portion of the Caribbean Sea on the 13th. It then moved north of west into the Gulf of Mexico on the 18th. The storm passed over Cuba on the 17th, where it was very severe. On the 19th it had appeared on the Gulf coast at several points in Texas, notably at Indianola, where at midnight the wind was blowing northeast, 40 miles, and in eight hours had increased to 72 miles. The storm was raging at 7 a. m. on the 20th. The wind was at that hour northeast, 49 miles, at Galveston, and northeast, 20 miles, at San Antonio. At 2:40 p. m., at San Antonio, the barometer registered 29.03, with a wind velocity estimated at over 80 miles per hour. The storm center was over San Antonio at 3 p. m., and the storm passed away with southeast winds.

The damage was most severe at Indianola, where no house remained uninjured, and many were swept away. Those which remained standing were generally in an unsafe condition. Among the buildings destroyed was the Signal Office, the observer losing his life in attempting to escape. More than 20 other lives were lost at Indianola. In Galveston the damage to property was estimated at $150,000, and more than 160 houses were damaged or destroyed. At Victoria 40 buildings, including 6 churches, were totally destroyed, and a loss of $100,000 was reported. Other towns in this region suffered to a more or less extent, and some interior towns felt the force of the storm to the extent of considerable losses.

6. *The Martinique cyclone of August 18, 1891.*—One of the most disastrous of West Indian cyclones, but which was confined to the region south of latitude 25°.

The storm continued four hours at Martinique, from 6 to 10 p. m. During the day there was a fresh northeast breeze, with a rapidly falling barometer, the wind steadily increasing in force. The storm struck the island at 6 p. m., the wind veering from east-northeast to south-southeast, and was most severe from the latter point; it was accompanied by thunder and lightning, and at its conclusion there were two distinct shocks of earthquake at intervals of five seconds. Two immense waves were noted in the vicinity of Caraval Rock (from a calm sea), passing from the direction of St. Lucia. The storm is charted in the Monthly Weather Review for August, 1891, as follows:

> 18th, Martinique.—Passing in a north-northwesterly course it was midway between Martinique and Porto Rico on the 19th; north of Grand Turks Island, West Indies, about midnight of the 21st; over Crooked Island, Bahamas, evening of 22d, and on the 24th was south of Cape Florida, latitude 24.5°, longitude 60°.

This storm did not affect any portion of the coast of the United States, though the reports at hand indicate that it moved westward with diminished energy over extreme southern Florida on the 24th, passing thence into the Gulf of Mexico. Its greatest severity was felt on the Island of Martinique at sea level, the elevated plains escaping with the minimum of damage. Seven hundred lives were lost at Martinique, and property to the value of $10,000,000 was destroyed. Some 50 vessels were wrecked, including sail of all classes. At Grand Turk 3 persons were drowned, the property losses being confined to small houses and sailing vessels.

7. *Hurricane of August 25–30, 1893.*—This was the very destructive hurricane which devastated the sea islands off the coasts of Georgia and South Carolina on the 27th and 28th, and which passed into Canada on the 30th.

The depression was felt as early as the 22d in north latitude 22°, west longitude 56°, where an uncommonly low pressure, 28.70, was reported, the storm being already fully developed. In the Weather Review account for the month it was stated that "its earlier history is yet quite problematic, but it is likely to be similar to that of the great Nova Scotia hurricane of August, 1873, started by a flow of dry air from northern Africa westward into the ocean."

The storm followed the general track of West Indian cyclones, save that it was developed in a higher latitude. The center had reached the Bahamas by the morning of the 26th, passing 100 miles northeast of Nassau, although the heavy waves which extended outward in all directions, from a hurricane center, were noticeable on the 25th at Savannah, Ga. On the 26th, at 8 p. m., the storm was central northeast of Jupiter Inlet, and on the afternoon of the 27th the center had reached the Georgia coast, the storm carrying death and destruction in its path. By 3 p. m. of the 28th the center was northwest of Charlotte, N. C., and on the morning of the 29th was near Oswego, N. Y., having moved 450 miles in twelve hours. Twelve hours later it was a little east of Quebec, possibly within the borders of Maine, and the next morning had moved into the St. Lawrence Valley; it was probably broken up in the vicinity of Newfoundland on September 1.

This was one of the most destructive storms to life and property that has visited the South Carolina and Georgia coasts in many years. The storm struck the islands in the vicinity of Charleston, S. C., and Savannah, Ga., on Sunday, the 27th, and from the fact that it was accompanied by a tremendous wave which submerged the islands, the loss of life was appalling, while the value of property destroyed ran into millions. Beaufort and Port Royal, S. C., felt the effects of the storm probably to a greater degree than other localities, although the destruction between Tybee Island, Ga., and St. Helena Island, S. C., was general. The money loss first and last, doubtless, amounted in the aggregate to $10,000,000, and at least 1,000 people, largely negroes, lost their lives.

Harper's Weekly for September 16, 1893, contains the following statements which are interesting:

> The best built houses in Savannah were drenched inside and shaken without. * * * Savannah was severely hurt, but her distance from the sea, the fact that she is landlocked 18 miles up the river, closely built, resting upon a bluff 45 feet above the water level, gave her some immunity from the ravages inflicted upon Charleston and

> Port Royal. Her parks and shade trees were damaged; roofs along the bay were torn away; the Tybee Railroad (17 miles) was almost a total wreck. * * *
>
> Port Royal harbor is broad and exposed. That city, with the beautiful residence town of Beaufort, was swept and battered, and the work of repair must be long and costly. Port Royal received the full shock of the storm. It was off Port Royal the steamer *City of Savannah* was wrecked. The Government dry dock is a wreck. Phosphate works are dismantled and the sea rolled over railroad tracks and piers.
>
> The ravage at Charleston was terrific. The loss to shipping off Tybee Island was greater than elsewhere, because Savannah's shipping is larger than all southern ports combined. * * *
>
> Hundreds of corpses were strewn along the farms, unknown save to the vultures which flocked about them. Whole families are wiped out in some places. The coroner has sworn in an army of deputies and these are hunting for the dead.

8. *Hurricane of August 7, 1899.*—This hurricane appeared east of Martinique on the morning of August 7, 1899, and during the afternoon and night of that date devastated the more southern of the Leeward Islands of the Lesser Antilles. During the 8th the storm caused the loss of hundreds of human lives and destroyed millions of dollars worth of property in Porto Rico. Moving thence north of west the disturbance crossed the Bahama Islands during the 11th and 12th, attended by a considerable loss of life and property, and from the 13th to the 17th skirted the South Atlantic coast of the United States, after which it disappeared in the direction of Newfoundland. At Porto Rico and at Hatteras, N. C., where its vortex passed near regular reporting stations of the Weather Bureau, the hurricane was of exceptional severity, and at Hatteras, N. C., it was the most severe storm within the recollection of the oldest inhabitants.

SEPTEMBER HURRICANES.

1. *Cyclone of September 26 to 27, 1874.*—Very generally compared to the hurricane of 1854, described on another page.

On the 25th the storm center was reported south of Louisiana, possibly nearer Yucatan or Mexico; during the night of the 27th and 28th the center passed in a northeasterly direction over upper Florida to the coast of Georgia, pursuing a track medial between those followed by storms Nos. VI and VII of September, 1873, as charted in the Weather Review for that month.

The track of the storm followed a generally north-northeasterly direction. As charted it was south of Lake City, Fla., on the 27th at 11 p. m.; the morning of the 28th it was north of Jacksonville, Fla.; on the afternoon of the 28th it had passed into North Carolina; on the morning of the 29th was west of Norfolk, Va., when it crossed Chesapeake Bay, and on the afternoon of the 29th had passed New London, Conn.; on the morning of the 30th the center was in Maine at a point due east from Mount Washington, and by the afternoon of the 30th had passed over Canada and was lost sight of at the mouth of the St. Lawrence. The highest winds were: Savannah, Ga., northwest, 36 miles; Tybee Island, east, 60 miles; Charleston, S. C., east, 51 miles, and northwest, 48 miles; Cape Hatteras, southeast, 75 miles; Wilmington, N. C., southeast, 45 miles, and southwest, 50 miles; Cape Henry, 50 miles. Lowest barometric pressure: at Charleston, S. C., 1 p. m., 28th, 29.06; at Portland, Me., 7:35 a. m., 30th, 29.05; at Boston, Mass., 4 a. m., 29.13, and at Eastport, Me., three hours later, 29.20. The amount of losses on account of the destruction of property was not reported.

2. *Hurricane of September 15, 1875.*—Referred to in the Weather Review as "the most severe which has occurred in the United States since the establishment of the weather service."

First observed in latitude 13°, longitude 17°, thought to have originated east of Barbados, where a severe storm occurred on the morning of the 9th. On the 12th the storm had reached the eastern portion of Cuba. Violent hurricane raged at Santiago de Cuba on the 13th; on the morning of the 14th the center of the disturbance had passed to the westward of Key West, Fla., and Havana, Cuba. At Indianola, Tex., the wind had increased to a gale at noon of the 15th, and by midnight was blowing north-northeast, 60 miles. Hourly observations taken from 1 a. m. to 5 p. m. showed the wind fluctuating, but gradually increasing, from 56 miles to 82 miles. About 5:15 the registry was 88 miles, when anemometer cups were carried away. The tide rose rapidly through the night of the 15th, the water breaking over the beach, and on the morning of the 16th was rushing in torrents through the streets. The local reporter states that by the night of the 16th "the volume and immense velocity of water pouring through the streets was truly terrible." The rain and wind increased up to midnight, when the wind velocity was estimated at 100 miles. The tide began to abate soon after midnight, the wind gradually backing to north and northwest, and a little later was sweeping out to the bay with irresistible force from the overflowed country extending miles inland. This was a new source of danger, as the buildings which had withstood the effects of the northeast storm, though racked and weakened, were unable to stand against the terrific force, in a cross direction, now brought to bear upon them. The morning of the 17th opened cool and cloudy, with a gale still blowing from the northwest, when it was known that three-fourths of the houses in the town had disappeared, with a loss of 176 human lives.

By the afternoon on the 17th the storm center was north of Galveston, Tex., when its course changed to easterly. On the morning of the 18th it was in the vicinity of the Mississippi River, when its course again changed to northeast, cutting the coast line on the morning of the 19th just above Norfolk, Va. During the easterly movement the center of the depression gradually changed to an elongated ellipse and the velocity of rotation was materially retarded, while the center remained on the continent.

3. *Hurricane of September 12–17, 1876.*—The storm center of this cyclone approached the Windward Islands from the southeast on the 12th; passed over Porto Rico on the 13th, with great destruction to property and crops; barometer at San Juan, 8:30 a. m., 29.49; wind north-northeast. Light hurricane reported at Santiago de Cuba on the 14th, which struck the Bahama Banks on the 15th, passing close to the east coast of south Florida. On the 16th it was about due east of Savannah, Ga., striking the North Carolina coast on the 17th in the early morning, though its near approach was perceptible late in the afternoon of the 16th. The anemometers at Wilmington, N. C., and Cape Lookout at the height of the storm, when both were disabled, recorded, respectively, north, 60, and southwest, 73 miles. At Hampton, Va., the lowest reading of the barometer was 29.10 at 1.20 p. m. of the 17th, the wind veering from northeast to southeast, and about three hours later, to south. At Washington, D. C., the barometer registered 29.15 at 4:35 p. m. One hour later the wind shifted from east to west, with a maximum velocity of 36 miles. In the passage of the storm along the south Atlantic coast, especially from the 16th to the 18th, very heavy easterly gales prevailed from Hatteras to Cape Cod. A peculiarity of this storm was its deflection to the northwest instead of the northeast, after striking the Atlantic coast, accounted for by an area of decidedly high pressure north of the Alleghenies on the 17th, and consequent heavy rains over the Middle States, with northwest winds.

4. *Tropical hurricane of September 21 to October 5, 1877.*—On the 21st the storm passed over or near Barbados, St. Vincent, and Grenada; 22d and 23d was 250 miles south of Porto Rico; 23d over Buen Ayre and Curaçao, where destruction to the extent of $2,000,000 and large loss of life was reported. In the City of Curaçao the most solid buildings were swept down by the waves. On the 28th it passed, in a northwesterly course, about midway between the west end of Cuba and the coast of Honduras. The vortex of the storm struck the coast of Florida near St. Marks at 11 p. m. on October 2, showing very slow progress. The wind reached a velocity of 66 miles per hour at 5:15 a. m. of the 3d at St. Marks, the tide rising 12 feet above the mean; barometer at 6:15, 29.17, wind southeast, gradually veering to southwest. High water was reported at Jacksonville, Fla., on the 2d. The storm passed northeastward over Georgia on the 3d, with the barometer at Augusta at 11 a. m. 29.35. On the night of the 3d and the morning of the 4th it passed over the Carolinas and Virginia, southeast gales prevailing along the coast. The storm was terrific in the vicinity of Albemarle Sound, the attending floods carrying away all the bridges and wharfs; crops were severely damaged along the James River. It passed Chesapeake and Delaware bays on the 4th, wrecking several vessels. The night of the 4th it appeared along the north shore of Long Island, and on the morning of the 5th the storm

center was about two degrees south of Cape Cod; at midnight it was four or five degrees southeast of Cape Breton.

In southeastern Pennsylvania, northern New Jersey, and along the Hudson River passenger trains were wrecked by washouts, resulting in great loss of life and property. In the region of Long Island the storm was very severe, several vessels having been wrecked. The damage in the Southern States traversed by the storm resulted largely from freshets and high tides, which were particularly destructive to cotton and rice crops.

5. *Tropical cyclone of September 1-13, 1878.*—This storm is particularly interesting, not only on account of its unusual track, but on account of its force and the attendant destruction of property throughout its course, which began near the Island of Trinidad, traversing the south Atlantic coast States, and proceeding almost due north to the Great Lakes, where it was very severe, finally disappearing in Canada.

It originated considerably to the eastward of Trinidad (probably near the Cape Verde Islands) and was central over that island at midnight of the 1st and 2d, when the storm began about 7 p. m. of the 1st and continued over twenty hours. Lowest reading of the barometer, 29.05, wind veering from northwest to southwest, and 7 inches of rainfall recorded; earthquake shocks also reported. On the night of the 2d and 3d it was central in latitude 15° north, longitude 68.5° west; on the 4th passed over Haiti and Santo Domingo; entered Cuba the night of the 4th and 5th near Guantanamo, leaving it near Cardenas. Although the center of the storm passed Cuba on the night of the 6th and 7th the barometer continued low until the 11th. On the 7th the storm entered Florida east of Key West, and during the next three days, up to the 10th, it slowly moved in a northerly course over the middle of the State. The gale was at its height at Jacksonville on the 10th, with the wind northeast, 40 to 48 miles. The vortex probably moved over Tybee Island on the 11th, though the gale lasted at this point from the 7th to the 12th. The total movement of air from the 8th to the 12th, inclusive, was 3,474 miles, and the total rainfall 5.61 inches. The center of the storm was located in South Carolina on the afternoon of the 12th. At 11 p. m. of this date a belt of low pressure extended from the Carolina coast to Lake Erie, the lowest pressure on the morning of the 13th being recorded at Buffalo, N. Y. The following wind velocities were reported at cities in the Lake region: Sandusky, Ohio, northeast, 48 miles; Cleveland, Ohio, west, 48 miles; Erie, Pa., west, 48 miles; Buffalo, N. Y., southwest, 45 miles; Rochester, N. Y., west, 30 miles. The storm passed off into Canada on the 13th.

This cyclone was particularly destructive in Trinidad where it destroyed buildings, bridges, and other structures, wrecked all vessels in the harbor and swept away entire plantations. Severest storm in forty years. Similar destruction was recorded in Haiti and Santo Domingo, where there was considerable loss of life, particularly in the towns, and where entire coffee and cocoa crops were destroyed in some localities. In Cuba the storm was attended with great and destructive inundations and remarkably heavy rainfall.

In Georgia and South Carolina there were likewise floods and inundations, attended with great destruction of property. The Georgia rice crop was damaged to the extent of $400,000. In the cities streets were flooded and business was suspended.

To the northward, over a wide extent of country, rivers and streams were dangerously swollen, resulting in washouts and damage to embankments, bridges, and railway trestles, and to docks and wharfs on the water front, while the farmers suffered everywhere. Stock, lumber, hay in the stack, and crops, generally, were washed away; and in town and country alike all kinds of property was destroyed by the terrible floods. The same widespread destruction attended the passage of the storm through Canada, as shown by the reports from Canadian observers.

6. *Hurricane of September 2-15, 1882.*—The movement of this storm was first noted at 10 a. m., September 2, at Grand Turk Island, with the barometer indicating 29.79, and wind strong northeast, shifting on the 3d to strong southwest. The center passed south of Isabella de Sagua, Cuba, during the evening of the 4th; at Cienfuegos, 11:30 a. m., on the 5th, the barometer had fallen to 29.13; wind,

west-southwest, blowing with great force; vortex went south of Havana between 12:30 a. m. and 2 a. m. of the 6th, wind east-northeast, 67 to 85 miles. After leaving the Island of Cuba the hurricane began to recurve toward the north and was encountered by the ship *City of Alexandria*, between 6 and 7 p. m. of the 6th, in latitude 22.5° north, longitude 85.4° west. The *City of Alexandria* on the 10th, 11th, and 12th, became again involved in the storm after it had recurved to the northeast. From the 6–10th the storm was encountered by many vessels while recurving to its north-northeast course before striking the coast of the United States. On the 9th the storm center was not far distant from Port Eads, La., where, during the day, the barometer fell to 29.39, with the wind northeast, 92 miles; the vortex passed just east of Pensacola, Fla., at midnight, with barometer 29.35. By the 10th the storm had increased in size, but decreased in energy, and had moved in a northeasterly track over Alabama, Georgia, and South Carolina. At Savannah, Ga., the barometer stood 29.56, and at Charleston, S. C., 29.60. The storm crossed North Carolina on the 11th in a northeasterly path, and still showed great energy. While the storm track left the coast on the afternoon of the 11th, the northern coast cities felt its influence by high winds, resulting in considerable damage to shipping. The storm track was about two degrees east of Cape Cod on the morning of the 12th, and by afternoon had again struck the continent near Halifax.

Considerable damage was reported in Cuba, particularly at Villa Clara and Cienfuegos. In Tuskeegee, Ala., 1,000 trees were blown down and crops damaged to the extent of $50,000. At Port Eads, La., the railway was destroyed and the jetty walls badly damaged, and New Orleans, La., likewise felt the force of the storm. The damage was slight at Savannah, Ga.; at Athens, Ga., many trees were blown down and some property washed away. The losses at Cedar Keys, Fla., footed upward of $100,000, and in other portions of Florida there was more or less destruction to property and to crops, particularly cotton. In South Carolina some buildings were destroyed and crops injured, chiefly in interior towns. Similar reports come from Virginia, the losses being considerable along the James River, which broke over its banks. In New England, coast cities reported high winds, with torrents of rain and some damage to shipping. Timely warnings had been sent out from the Signal Office, however, through which a vast amount of destruction to shipping was prevented by the vessels remaining in harbor. This saving was estimated by the office to have amounted to $13,000,000, as was afterwards reported by station observers.

7. *Hurricane of September 4–5, 1883.*—Referred to as the September northern cyclone (Jamaica Meteorological Observations, Vol. I).

First observed at St. Pierre, Martinique, afternoon of the 4th, and by the morning of the 5th had entered the Caribbean Sea. Passed over Dominica 1 a. m. of the 5th, with barometer 28.98, wind north-northeast and south-southwest; was accompanied by a shock of earthquake; was encountered by vessels in the Mona passage on the 5th. During this date the center moved slowly westward south of Porto Rico and by midnight the vortex was near Santo Domingo; on the morning of the 6th had crossed north latitude 20°, and was just eastward of Cuba; on the 7th was in the Bahamas, on a line a little south of east from Havana. The cyclone passed over Nassau at 2 p. m. on the 8th, with the barometer 28.87, wind north-northwest and west, and on the 9th was probably central near Abaco Island. During its progress from the Bahamas the center did not appear to deviate from a northerly course as its violence was not felt on the coasts of Florida, Georgia, and South Carolina, nor by vessels that were east of the seventy-fourth meridian, though the storm was very disastrous to vessels between Hatteras and Wilmington, N. C. The storm showed considerable force along the North Carolina coast on the 9th, and at Fort Macon and Cape Lookout, N. C., the wind was blowing from northeast, 60 miles an hour, on the morning of the 10th, and by afternoon of that date was blowing 75 miles an hour. Other coast cities also reported high winds, high tides, and heavy surf. Central near Cape Hatteras on the 11th, when it passed north to Nova Scotia. After the 10th, 11th, and 12th the winds remained high over the ocean from west longitude 75° eastward to the sixtieth meridian, but the pressure increased to 30.00 and above. While not a very destructive storm it did great damage to shipping in

Martinique and considerable land damage at Dominica. In the Bahamas over 100 vessels were wrecked or disabled and at least 50 lives were lost. In North Carolina there was some damage to buildings and crops and some vessels were driven ashore, many having been saved, however, through the timely warnings of the Signal Office. Immense damage was reported at Halifax.

8. *The great Cuban cyclone of September 1–7, 1888.*—This storm did not enter the United States, but pursued a westerly course from latitude 20° north to longitude 63° west, striking the northern coast of Cuba in longitude 77° west, passing to the southwestern end of the island, and pursuing a nearly west-southwest direction, swept the northern coast of Yucatan, striking the Mexican coast between Vera Cruz and Coatzacoalcos about two degrees south of latitude 20°, and the same west of the ninety-fifth meridian. The chronology of the storm is as follows: First indications were noted in the northeast trade wind belt east of the sixtieth meridian on the 30th and 31st of August; noon of September 1 found the hurricane center north of the western end of Porto Rico; on the 2d it was over Turks Island, and by noon of the 3d to the northward of Great Inagua Island, with the barometer 28.70. At noon of the 4th the center was off the coast of Cuba just east of Sagua, the barometer registering 28.90 at 9 o'clock in the morning. The center left the western extremity of the island during the 5th, and on the 6th was over northern Yucatan, reaching the Mexican coast by the night of the 7–8th. This storm was remarkable both on account of its exceptional energy and by reason of the abnormal path it pursued after having advanced toward the eightieth meridian.

At Turks Island more than 250 houses were destroyed, with other valuable property, including 400,000 bushels of salt; and 21 human lives were lost. The greatest destruction was reported from Cuba, where the losses to property ran up into millions of dollars, and the loss of 800 lives was recorded. The principal buildings in the cities were destroyed, and whole towns near the seaboard swept out of existence by the gigantic seas which overwhelmed them. In Mexico, particularly along the coast, there was also great damage.

9. *Tropical storm of September 6–14, 1888.*—The great Cuban cyclone was immediately followed by a depression which was central over the Bahamas September 4. It was observed near Jupiter, Fla., afternoon of the 7th, moving slowly northwestward, recurving near latitude 30°, in the vicinity of Cedar Keys on the night of the 8th. On the afternoon of the 10th, central near Norfolk, Va., after which it followed the Middle Atlantic and New England coasts, attended with dangerous gales, and proceeded as far as Boston, Mass. From New England it moved directly northward to the St. Lawrence. Lowest pressure, 29.50, at Cedar Keys, Fla., on the 8th, with the wind 60 miles. The Jamaica Meteorological Observations for September, 1888, says "that this storm vanished midway between Newfoundland and Ireland." No special damage was reported.

10. *The St. Thomas-Hatteras hurricane of September 3–12, 1889.*—From the reports of vessels sailing to the eastward of the Windward Islands, this storm is thought to have been central September 1 in latitude north 14° and longitude west 57°. Passed over St. Christopher during the night of the 2d; barometer 29.50, wind northeast. The storm was central near St. Thomas on the 3d, and near to and north of Porto Rico on the 4th, while on the 5th it had moved about two degrees in a northwesterly curve away from Porto Rico. Marine observations on the 6th indicated two centers of disturbance, one passing northward from north latitude 22°, west longitude 67°, the other passing west-northwesterly from the same point. The latter depression was central in north latitude 28°, west longitude 77°, on the 6th, but was traced no farther, while the easterly disturbance was central in north latitude 29°, west longitude 66°, on the 6th. It now recurved to the northwest, and was one and one-half degrees farther north and two degrees farther west on the 7th. On the 8th it appeared in north latitude 32° and west longitude 68°, and on the 11th the center had reached north latitude 38°, west longitude 67.5°, being charted eastward of Chesapeake Bay. The storm track at this point recurved sharply to the southwest, apparently forced to this course by the area of high pressure to the northward, and was some distance off Hatteras, N. C., on the 12th, its course being traced no farther. Considerable disturbance was noted all along the coast from North Carolina to New England, with

violent storms and high tides. The losses footed up between two and three million dollars, falling heavily upon the railroad and ship owners. The storm was especially severe in the West Indies, and there were reports of great damage to crops over many of the islands lying in its track.

11. *Hurricane of September 26–30, 1896.*—First reported from the northwest of Cuba on the 26th. By the morning of the 28th the center had moved to the Florida coast, wind southeast at Key West. By the 29th it had entered southwestern Georgia and was increasing rapidly in intensity. By 8 p. m. of the same date it was central over Lynchburg, Va., barometer 29.30, the storm reaching the District of Columbia about three hours later. On the morning of the 30th the storm center had moved to Lower Michigan, when its course was deflected and it passed to Lake Ontario and the St. Lawrence Valley, in a northeasterly direction. Its passage from Key West to Canada occupied twenty-four hours, showing a uniform rate of progression of 46 miles per hour. The path of its destruction did not extend more than 50 miles in width in any part of its course. The greatest violence was manifested in Florida during the early morning of the 29th. A second period of violence began in Virginia about 9 p. m. and lasted until midnight in Pennsylvania. Following a lull, there was a third renewal of intensity during the early morning hours of the 30th in Cayuga and Cortland counties, N. Y.

The loss of life and property in the States traversed by the storm is given in the following table from the Monthly Weather Review for September, 1896:

State.	Loss of life.	Loss of property.
Florida	68	$2,225,000
Georgia	25	933,000
South Carolina	5	25,000
North Carolina	0	20,000
Virginia	5	695,000
District of Columbia	1	443,000
Maryland	8	500,000
Pennsylvania	2	2,140,000
New York	0	50,000
Total	114	$7,031,000

This storm is remembered as one of the most severe of the West Indian hurricanes that has swept the country, its severity being specially marked in Florida and Pennsylvania, while in the District of Columbia it was one of the worst storms on record.

Hurricane of September, 1854.—Several hurricanes of unusual violence, during the part of two decades, have been compared to the hurricane of 1854. Several such references are found in the Monthly Weather Review. Authorities for the 1854 hurricane are Baldwin, Pasey, and Blodgett (page 400, —— Climatology).

The storm extended from September 6 to 14. First noted off Cape Florida on the 6th; at Jacksonville, Fla., on the 8th; appeared at Charleston, S. C., on the 9th; Norfolk, Va., on the 10th, and Boston, Mass., on the 11th. The central line was doubtless some distance off the coast, though the interior was visited with tremendous rainfall. Terrific gales marked its passage in the Gulf Stream. Barometer at Savannah, Ga., 29.04. The general direction of the wind was northeast. At sea the series of gales continued to latitude 54° and longitude 35°, with many wrecks of vessels. Washington, D. C., Philadelphia, Pa., and New York, N. Y., felt the effects of the storm, and in Philadelphia many buildings were prostrated. At Charleston, S. C., and Savannah, Ga., it was more destructive, as regards inundation, than any previous storm for many years:

> The wind was strong and constant from the northeast through the 6th and 7th and the morning of the 8th, when it changed to southeast with equal severity. The waters subsided on the 8th and 9th, with strong southwest winds. It was a hurricane at northeast through the whole of the 8th at Savannah.—*Blodgett.*

No accounts showing losses of life and property are available, though reference is made to a paragraph in the Monthly Weather Review for August, 1881, relating to the hurricane of that month and year, in which a comparative reference is made to the 1854 storm:

Damage to property in the city (Savannah) is estimated at $1,500,000. On the morning following the storm there was presented the most terrible scene of wreck, ruin, and death that was ever witnessed within the memory of the oldest inhabitant. The memorable storm of 1896 was not so violent or prolonged.

12. On September 10 and 11, 1898, a hurricane visited the Windward Islands of the West Indies. This storm was particularly destructive throughout the Island of Barbados, where 83 persons were killed, 150 injured, and property to the estimated value of $2,500,000 was destroyed. At St. Vincent and St. Lucia the violence of the hurricane during the 11th equaled, or exceeded, that manifested at Barbados the night of September 10. After the 11th the hurricane center moved northwestward with a very marked loss of strength, and finally disappeared east of the Bahamas during the 14th of September.

13. On the morning of September 8, 1899, a storm of pronounced energy appeared east of the Island of St. Kitts, from which position it moved northwestward until the 10th, when it began to recurve to the northward. During the 11th and 12th the recurve changed to the northeastward and the storm passed over the Bermuda Islands during the night of the 12–13th. This storm was quite severe over the more eastern islands of the Leeward group of the Lesser Antilles during the evening and night of the 8th, and also over the Bermudas during the night of the 12th.

14. *The Galveston, Tex., cyclone of September 8, 1900.*—This was the severest and most destructive hurricane in the storm annals of the Western Hemisphere. It apparently originated in the vicinity of the Windward Islands of the West Indies August 31, and from that region moved westward over the Caribbean Sea during the first three days of September without evidence of marked energy. During the 4th it recurved northward over Cuba, passing just east of Havana, and during the 5th advanced slowly toward the extreme southern point of Florida. During the day and night of this date the storm acquired marked strength and caused the loss of a number of vessels, mostly small sailing craft, on the keys and coast of southern Florida. It did not, however, attain hurricane intensity until the 6th, when it began its westward course across the Gulf of Mexico. Only one vessel is known to have encountered the hurricane during its course over the Gulf and this vessel was the Cromwell Line steamship *Louisiana*. The captain of the *Louisiana* reports that he passed through the center of the storm at 1 p. m. of the 6th when about half way across the Gulf, on a course from New Orleans to the southern point of the Florida Peninsula. At that hour his barometer showed a reading of 28.75 inches, and he estimated the wind velocity at over 100 miles an hour. The gales along the middle coast of the Gulf of Mexico, while severe, were not especially destructive, and it was not until Galveston was reached, during the evening of the 8th, that the full force of the storm was again experienced. The center of the vortex of the hurricane passed some miles south and west of Galveston shortly after 8 p. m., seventy-fifth meridian time, attended at Galveston by a barometer reading of 28.48 inches. This is the lowest reading of the barometer ever reported in the United States. After having registered a wind velocity of 100 miles an hour the anemometer cups were blown away at 6:15 p. m. Between that time and 8 p. m. the wind reached an estimated velocity of at least 120 miles an hour.

In Galveston, out of a population of about 40,000, fully 6,000 were drowned or killed, $20,000,000 worth of property was destroyed, and not a building in the city escaped injury. The loss of life and property was caused principally by a storm wave which, in connection with the high water blown in by the wind, flooded the city and island of Galveston to a depth of 6 to 15 feet. Thousands of lives were saved through the action of the local Weather Bureau officials in disseminating, by every possible means, warnings of the character of the impending storm. At the risk of their own lives—and one of their number perished with his family—they warned the population to seek the higher parts of the city. After all that human endeavor could accomplish in this direction had been done the official in charge, Dr. I. M. Cline, reached his own home, which was an uncommonly strong structure, and gathered therein neighbors to the number of about 50 whose houses were less substantially built. A final wave 4 feet in depth, aided by the debris which was hurled by the wind and rushing waters, swept his house from its foundations and it collapsed, drowning or killing 32 of the 50 people who had gathered within its walls, one of the number being Dr. Cline's wife. The balance were storm tossed on the wreckage of buildings for three hours. That no vessels were wrecked, so far as is known, in the Gulf of Mexico can be ascribed to the fact that all ports and shipping interests were warned of the approach of the storm two days before it entered the Gulf from Florida and three to four days before it reached the central and west portions of the Gulf.

After passing inland from Galveston the storm lost strength rapidly and did not again acquire destructive force until it approached the Great Lakes. Crossing the Lake region it was attended by gales of great violence. Ample warnings of its approach, however, reduced the damage to a minimum. Moving eastward over the Canadian Maritime Provinces the storm gathered further strength and caused considerable destruction to land property and also to shipping in Nova Scotia and Newfoundland waters.

OCTOBER HURRICANES.

1. *Hurricane of October 21–24, 1878.*—This storm was developed south of Cuba, though little is known of its early history. Was noted at Havana on the night of the 21st. At 4:35 p. m., Havana, the barometer showed pressure at 29.67, wind northwest, 24 miles. Lowest barometer at Key West, Fla., 29.53, at 2 and 4:19 p. m., wind 54 miles during the morning. From a. m. to p. m. wind backed from northeast to northwest. Severe gale from east-northeast, backing to north, was reported off St. Johns Bar during the 21st and 22d, though the wind at Jacksonville, Fla., did not exceed 17 miles. During the 22d the vortex of the storm moved northward from the east coast of Florida to the coast of North Carolina, and at 11 p. m. the center was midway between Wilmington, and Cape Lookout, N. C. The storm began at Kittyhawk, N. C., 6:30 p. m., on the 22d, and the wind reached its maximum registered velocity of 88 miles, southeast, at 2 a. m. of the 23d, when the anemometer was carried away; barometer 29.06, wind shifting suddenly to southwest. Cape Henry and Norfolk, Va., wind shifted from southeast to southwest, during the night, maximum velocities 84 and 44, respectively. The storm center passed into New York State about noon of this date, when its northerly course was deflected to the eastward, and it passed into New England during the latter part of the day, and morning of the 24th, its severity being somewhat modified, it then disappeared into the ocean at a point between Boston, Mass., and Portland, Me.

The storm did considerable damage in Cuba, particularly at Havana, where buildings were blown down and shipping destroyed. It was particularly severe on Chesapeake Bay, especially between the mouth of the Patuxent River and Barren Island, where a steamer was sunk with loss of life, and several vessels were driven ashore. On Delaware Bay the storm was said to have been the most severe ever experienced, vessels of all kinds being driven ashore with loss of life. The wind blew 72 miles an hour in Philadelphia, Pa., injuring or totally destroying 700 substantial buildings; 8 vessels were sunk, and 22 badly damaged; the losses were estimated at one to three millions of dollars. High tides and inundations occurred all along the New Jersey coast, and in the interior, particularly in eastern Pennsylvania, there was great damage to property, and some loss of life. At New London, Conn., severest storm in forty years. Wind at Portland, Me., 70 miles, and anemometer cups carried away. Very high tides noted along the New England coast, with considerable damage to wharfs and shipping. The influence of the storm extended to the lower Lake region and the cautionary signals ordered on the 22d were justified.

2. *West Indian cyclone of October 8–12, 1882.*—The earliest notices of the development of this storm were received from scattered vessels indicating its presence in the Caribbean Sea from the 5th to the 7th, and probably near north latitude 15°, west longitude 82°, although it developed little energy until the 8th, when the center was near Grand Cayman Island, southeast of Havana. On the 8th the diameter of the cyclone greatly increased, and its presence was felt over the entire Island of Cuba and westward to the coast of Yucatan and the Gulf of Mexico. The center was passing over the western portion of Cuba on the morning of the 9th. At Pinar del Rio the violence of the storm was

first felt about 2 p. m. of the 8th, when the wind increased to hurricane force. The vortex passed over this point at 7:15 p. m. At Key West, Fla., 9 a. m. of the 9th, southeast gale and heavy rain were reported. At Jacksonville, Fla., on the 10th the wind reached a velocity of 44 miles per hour. The gale began at 4 p. m. on the 10th at Cedar Keys, Fla., though the first disturbance was felt on the 9th. On the morning of the 10th the wind was veering from northeast to east, gradually shifting during the day to southeast and south, with a velocity of 56 miles. The center passed into southern Georgia on the morning of the 11th, and by the afternoon was near Savannah, Ga. From this point the course of the storm followed the coast line to Cape Hatteras and passed off to the eastward on the 12th.

The storm was very disastrous in western Cuba, where the town of Pinar del Rio was almost destroyed. At San Juan and Martinez, Cuba, 1,500 warehouses and dwellings were destroyed. In the district of Guane the destruction of houses and tobacco storage buildings reached 2,000, and thousands of cattle were swept away. Similar reports of disaster and loss of human life were received from many other towns and localities.

The losses in the United States were comparatively light, and were confined to the extent of damage which usually follows the advent of high winds and flood, such as the prostration of trees, the destruction of growing crops, washouts on the railways, injury to water fronts in coast cities, and damage to unprotected shipping.

Through the timely warnings of the approach of this storm, sent out by the Signal Office, vessels to the value of over six millions of dollars were prevented from sailing.

3. *So-called Gulf hurricane of October 1-6, 1893.*—A small, violent whirl in the Gulf of Mexico on the 1st, the early history of the storm not being known. It developed rapidly, striking the Gulf coast on the same date, its destructive influence being felt from New Orleans, La., to Pensacola, Fla. It had reached the southwest corner of Alabama on the morning of the 2d, and was central in the northern portion of Alabama on the 3d. On the morning of the 4th it had reached the Atlantic coast line in North Carolina near Hatteras, and was dissipated in the Atlantic on the 5th.

Violent wind, heavy rains, and local storms attended its progress through the South Atlantic States, though the greatest amount of destruction and loss of life occurred in Louisiana, where the track of the storm passed between Port Eads and New Orleans. As the instruments used in the weather service were blown away, or destroyed, only an estimate of the maximum force of the wind was made, which placed the velocity at 100 miles an hour near Pointe a la Hache. The storm was accompanied by a tidal wave which engulfed everything before it, explaining the great loss of life reported, one local account placing it as high as 2,000. The canning interests suffered severely, and there was immense destruction to shipping, the property losses in the aggregate footing up millions of dollars. There was great suffering among the living in many localities, and in some instances, as on the islands, it was necessary to use for food dead animals and poultry that had perished in the storm. In the vicinity of Mobile, Ala., the storm was very severe, though unattended with the terrible loss of life recorded in Louisiana. In the marsh truck farm region nearly every house was swept away and the crops destroyed; 7 lives were lost. At Pensacola, Fla., considerable damage was done to the water front, and there were bad washouts on the railways. The influence of the storm extended to Savannah, Ga.

4. *West Indian hurricane of October 1-13, 1894.*—While this storm developed winds of hurricane force, reports of destruction are conspicuous by their absence, the storm being chiefly interesting on account of the great length of its course, with a very flat trajectory, and because it swept the Atlantic coast line from western Florida to the New England States. Its development was traced from a point off the coast of Colombia, South America. Following a northwesterly course from north latitude 14°, west longitude 78° on the 2d, it passed midway between Cuba and Yucatan on the 4th and 5th. It was in north latitude 27°, west longitude 88° on the morning of the 7th, when it swerved to the northeast and entered the United States at the western extremity of Florida on the morning of

the 8th, crossing South Carolina on the 9th, reaching the coast of New Jersey on the morning of the 10th, and by the evening of this date the severity of the storm was felt at Portland, Me. From this point its course was almost due north, and the morning of the 11th found it above north latitude 50°, west longitude 67°, in Canada, when it again swerved to east-northeast, and on the 13th was in north latitude 52°, west longitude 45°, in the Atlantic Ocean. Recorded wind velocities in Southern States, 30 to 80 miles; in New England States, 60 to 84 miles; very severe at Narragansett and Block Island, R. I. Timely warnings kept many vessels in port along the entire coast line.

5. *Hurricane of October 19-24, 1895.*—This was the only destructive hurricane that developed in the West Indian Islands during the month of October, 1895. The track of the storm at no time touched the Atlantic coast line in the United States, although the influence of the storm was felt at southern points in high winds.

On the 19th the storm was central south or southeast of Cuba. On the night of the 20th it crossed Cuba, and on the 21st was between Cuba and Nassau. Pressure at Havana, 29.74, and at Nassau 29.84 in the morning, and 29.62 at Key West, Fla., in the evening. On the 22d the center was between Nassau and the mainland, the pressure being well marked over Florida. Wind velocities of 55 miles per hour were reported from Jupiter and Key West, Fla., and 80 miles at Havana. Very high tides occurred on the south Atlantic coast, but no special destruction in the United States was reported. Timely warnings were given and many vessels remained in port that otherwise might have found themselves in positions of danger.

A NOVEMBER HURRICANE.

This record is not complete without reference to the destructive West Indian hurricane of November 17, 24-29, 1888. It was first noted on the 17th northeast of the Windward Islands, from whence it proceeded westward almost on the line of north latitude 23°, making its appearance in the Bahamas on the 22d. On the 22d its influence extended to the fortieth parallel, and after its recurve over the Bahama Islands it augmented in energy until the 26th, when minimum pressure falling below 29.00 was reported. On the morning of the 27th the center was just off the New England coast; on the afternoon of the same date it had passed into Maine, and by the 28th was in the British Possessions.

As early as the 25th the gale had developed a force of 66 miles an hour at Hatteras, N. C., and northwest 50 miles on the 26th at Norfolk, Va. At Atlantic City, N. J., on the same date, high winds prevailed with high tides, barometer 28.96 at 2 p. m. At New York, N. Y., the wind was northwest, 40 miles, on the 26th. The storm continued at New Haven, Conn., up to noon of the 27th, wind northeast, 51 miles. At Block Island, R. I., 3:25 a. m., on the 26th, the maximum velocity of the wind was 84 miles per hour. At Woods Hole, Mass., the storm continued until the evening of the 27th, with a maximum wind velocity at 2 p. m., northwest, 48 miles. High winds prevailed at Portland, Me., on the 25-27th; maximum velocity on the 26th, northeast, 36 miles. At Boston, Mass., the maximum velocity was northeast, 60 miles, at 1:35 a. m. of the 27th, but moderated to 36 miles at 8 a. m., then increased during the day to northeast and north, 48 miles. The storm was particularly severe on the Atlantic Ocean as reported by the vessels which felt its force. The damage to shipping was very severe all along the Atlantic coast from Hatteras, N. C., to Eastport, Me., and many vessels were wrecked or disabled. Norfolk, Va., suffered from both winds and floods, the damage to property in the city being considerable. In and around New York, N. Y., the damage was general, and it was stated that the losses would foot up millions of dollars. In New Haven, Conn., two houses were destroyed and telegraph and telephone wires wrecked. Similar reports came from Rhode Island and Massachusetts coast towns, vessels in the harbors dragging anchors, and, in some instances, smaller craft being driven ashore. In Portland and Eastport, Me., buildings, fences, trees, and shipping felt the fury of the storm, which, in the last-named city, was accompanied by snow, sleet, and heavy rain.

LOCAL DESCRIPTIONS OF HISTORICAL WEST INDIAN HURRICANES.

PORT OF SPAIN, TRINIDAD.

The only hurricane that has visited this island during the present generation, if I have been informed correctly, was in 1847, but I am unable to obtain any data bearing on the same.

ERNST T. GIBBS,
Observer, Weather Bureau, Port of Spain, Trinidad.

THE BARBADOS HURRICANE OF AUGUST 10, 1831.

There was no premonitory sign of this hurricane observed, except by one individual, which will be referred to later on, other than an extreme redness of the sky on the evening of the 10th. This appearance was not unusual, as it is frequently seen at this season of the year. The heat, however, had been very oppressive and intense for some days previous, but that was to be expected at the approach of the equinox. Rains set in early in the spring and had been quite general during the three months preceding the hurricane, July being especially wet. The weather, altogether, had been totally unlike that which preceded the storm of 1780.

The electric action during the storm was very unusual, at times being in the form of a livid flame and at others it came in the form of alternate sheets and forks. The hurricane lasted in its utmost fury from about midnight of the 10th until 8 a. m. of the 11th.

Calamitous as were the many tempests from which Barbados had suffered, the aggregate destruction produced by the whole combined was probably unequal to that effected by the hurricane of 1831. The hurricane of 1675, according to historical account, very much resembled it in appearance, duration, and fury, but the extent to which human life then suffered is not on record. The hurricane of 1780, fearfully tremendous as it was, is admitted to have been far inferior in force and less destructive to property.

Sunrise on the 10th was clear and at 10 a. m. a gentle breeze which had been blowing died away. After a temporary calm, high winds sprang up from the east-northeast, which also subsided. For the most part calms prevailed, interrupted by occasional sudden puffs from between north and northeast. At noon the heat increased to 87°, and at 2 p. m. to 88°, at which time the weather was uncommonly sultry and oppressive. At 4 p. m. the temperature was 86°, and at 5 p. m. the clouds seemed gathering densely from the north, the wind commencing to blow freshly from that point; then a shower fell, followed by a sudden stillness, but with a dismal blackness all round. Toward the zenith there was an obscure circle of imperfect light, subtending about 35° or 40°. From 6 to 7 p. m. the weather was fair and wind moderate, with slight puffs from the north, the lower and principal stratum of clouds passing fleetly toward the south, the higher strata, a scud, rapidly flying to various points. At 7 p. m. the sky was clear and the air calm, tranquility reigning until a little after 9 p. m., when the wind blew again from the north. At 9:30 p. m. it freshened and moderate showers fell at intervals for an hour. Distant lightning at 10:30 p. m. in the northeast and northwest. Squalls of wind and rain from the northeast, with intervals of calms succeeding each other until midnight. The thermometer in the meantime varied with remarkable activity; during the calms it rose as high as 86°, and at other times it fluctuated from 83° to 85°, this high stand of the thermometer near midnight under the tropics being without record.

After midnight the continued flashes of lightning were awfully grand and the gale blew fiercely from between the north and northeast. At 1 a. m. of the 11th the tempestuous rage of the wind increased, shifting suddenly from the northeast to the northwest and intermediary points. The upper regions were from this time illuminated by incessant lightning, but the quivering sheets of blaze were surpassed in brilliancy by the darts of electric fire which were exploded in every direction.

At a little after 2 a. m. the astounding roar of the hurricane, with wind from the north-northwest and northwest, can not by language be described. About 3 a. m. the wind occasionally abated, but intervening gusts proceeded from the southwest, the west, and northwest with accumulated fury. The lightning also having ceased for a few moments, only, at a time, the blackness in which the town was enveloped was inexpressively awful. Fiery meteors were presently seen falling, one in particular, of a globular form and deep red-blue hue, was observed to descend perpendicularly from a vast height and fell in Beckwiths square. A few minutes after the appearance of this phenomenon the deafening noise of the wind sank to a distant roar; the lightning which from midnight had flashed and darted forkedly, with a few and but momentary intermissions, now for a space of nearly half a minute, played frightfully between the clouds and the earth. The vast body of vapor appeared to touch the houses and issued downward flaming blazes which were nimbly returned from the earth upward. The moment after this singular alternation of lightning the wind began again to blow from western points with a violence beyond conception, hurling before it thousands of missiles, the fragments of every unsheltered structure of human art. The strongest houses were caused to vibrate to their foundations and the surface of the very earth trembled as the destroyer raged over it. The horrible roar of the wind, the noise of the tumultuous ocean, whose frightful waves threatened the town with destruction if all other elements might spare it, the clattering of tiles, the falling of roofs and walls, and the combination of a thousand other sounds, formed the most hideous din, which appalled the heart and bewildered, if not alienated, the mind. No adequate idea of the sensations which then distracted the mind and confused the faculties can possibly be conveyed to those distant from the scene of terror.

This unparalleled uproar continued without intermission until half past 4 in the morning, when the raging blast veered from the west and other points to the southward, with avalanches of rain accompanying. After 5 a. m. the storm now and then for a very few moments abated, the falling of tiles and building materials, which by the last dreadful gust had been carried to a considerable height, the shrieks of suffering victims, the cries of the terrified inhabitants, were clearly audible, awakening the mind to a distressing apprehension of the havoc and carnage which had been, and still were desolating the island.

At 5:30 a. m., after a dreadful gust from the southwest, the wind suddenly chopped around to the east, from whence it blew a moderate gale, changing to southeast in a few minutes after and blowing with hurricane force, but unaccompanied by those fatal gusts which from the western quarter had inflicted so much destruction. Torrents of rain fell at this time. At 6 a. m. the wind blew steadily and tremendously from the south, driving sheets of rain horizontally before it. This continued until 7 a. m., when the wind then from the southeast, was more moderate, but floods of rain still deluged the ruins of the town. Strong breezes from the east-southeast at 8 a. m.; after that hour the dense body of cloud began to break up, and at 10 a. m. the sun for a few moments darted its rays over a prospect of wretchedness and woe, more replete with real misery and sickness to the heart than the field of battle (after a sanguinary conflict) ever presented.

This hurricane came from the southeast of Barbados, the center passing slightly to the north of the island. It produced great damage in St. Vincent and St. Lucia, and slightly touched Martinique. On the 12th it arrived at Porto Rico; the Aux Cayes, Hayti, was nearly destroyed by its force, and Santiago de Cuba much injured. On the 14th it was at Havana, and on the 16th and 17th on the northern shores of the Mexican Sea. It blew a dreadful gale in New Orleans, La., on the 17th. The duration was six days from the time it commenced in Barbados until reaching New Orleans, La., a distance of 2,100 nautical miles.

The ships in the harbor were totally destroyed, being either blown out to sea or sunk at their moorings, 12 at least were driven high on the beach, total wrecks.

No portion of the island escaped the ravages of the storm, and, without particularizing, its effect can best be studied by consulting the value of the property destroyed, which is estimated at $7,397,532. This does not include the value of the government property and principal shipping destroyed.

According to official returns the total number of persons killed outright is, 1,477; wounded, 310, of which 114 died afterwards. To this should be added 48 soldiers killed, and 242 wounded in the ruins of the garrison barracks. It is thought that the total number killed and wounded was not reported to the government, and it is estimated that at least 2,500 were killed or died from results of wounds.

Freaks of storm.—A piece of lead weighing 150 pounds was carried to a distance of more than 1,800 feet, and another piece, 400 pounds in weight, was lifted up and carried 1,680 feet. Many instances are reported of shingles and pieces of tin being forced by the wind into trunks of hard wood trees.

Generally the surface of the ground was denuded of vegetation, appearing as if a fire had passed over it. The few trees left standing were stripped of all foliage.

It is stated that an earthquake accompanied this storm, but nothing authentic can be found on the subject, other than a statement that many walls were covered with cracks and fissures.

Mr. Benjamin Gittens, Barbados, appears to have been the only person to observe any premonitory signs of the approach of this hurricane, and these were: 1st. The darting forward of the clouds in divided portions with fleet irregular motion, not borne with the wind, but driven as it were before it. 2d. The distant roar of the elements, as of wind rushing through a hollow vault. 3d. The motion of the branches of trees, not bent forward as by a stream of air, but constantly whirled about.

While this storm was passing over the West Indies on the 11th, 12th, and 13th, objects which were of whitish color appeared to be of light blue, so marked as to attract the attention of all the inhabitants.

From Schomburgk's History of Barbados. Reid on Storms, was also used, these being the only authorities from which a description of this storm could be obtained here.

P. McDonough, *Observer, Weather Bureau.*

HURRICANE AT ROSEAU, DOMINICA, W. I., 1834.

In the history of Dominica about twenty hurricanes are recorded since the year 1765. Among these, four stand out preeminently as very destructive visitations. They occurred in 1806, 1813, 1834, and 1883. Concerning the first two nothing authentic can be learned, except that in 1806 the Roseau River overflowed, inundated the capital and

131 persons were killed. Much information can of course be obtained of the last one mentioned, as it is of comparatively recent occurrence, and many eye witnesses are alive.

It is found, on inquiry, that the storm of 1834 is generally accepted as the most destructive one that ever visited the island. Unfortunately, there are no intelligent living witnesses of this storm, and the only record which can be found is contained in some notes left by the Hon. John Imray, M. D., who was government medical officer of the island at the time, and a man of reputed high scientific attainments. From his notes the following description is made:

"This terrible hurricane happened on the night of September 20, 1834. The sun had set very red that evening, but the day had been cool, with occasional showers, and nothing appeared remarkable in the weather previously to lead to the supposition that so tremendous a visitation was at hand. As soon as the sun had set the wind veered round to the north and northeast, with light showers until 10 o'clock. It then suddenly increased in violence, and the people were obliged to have their houses shut up immediately. Each gust came with greater force than the preceding one, until it blew a complete hurricane, and really frightful it was—the wind roaring and rattling over the house with a deafening noise, making the solid stone building shake to its foundation. A little after 12 o'clock the wind moderated and soon afterwards it was almost a dead calm—a treacherous calm it proved." Dr. Imray went out during the calm and by the moonlight could see, though dimly, trees and houses blown down. In his own yard a beautiful mango tree had been torn up by the roots, and a large silk cotton tree (believed to be the largest on the island, and which is standing to-day) was a branchless trunk. Two of his windows had been blown in and part of the roof ripped off. Everything was in the direst confusion and the rain pouring in in torrents. The wind by this time had again begun to blow, this time from the opposite direction—the south. In a few moments on the hurricane came again, from the south and southwest, with greater fury than before; it continued to rage until near daylight. As soon as the wind would allow, he again went out to see what further damage had been wrought.

The scene of desolation that daylight disclosed was awful. The streets were flooded with water and strewn with shingles and rafters, and the parts of roofs of houses, trees blown down and lying across the streets, houses entirely turned upside down and shifted into the middle of the streets, many of them in ruins. All the houses along the bay side were injured, partly by the surf which rolled up in tremendous waves. There were many hairbreadth escapes from death. The next day it blew a heavy gale, with rain, and the people were in expectation of having another blow but it did not come.

The accounts, as they came in from the country, were distressing. The vessels that were at anchor in Prince Ruperts and Soufriere bays were driven ashore and 11 sailors in all drowned. . An American schooner went ashore at Grand Bay and not a soul was saved.

Here follows some detailed accounts of the destruction wrought by the storm and the number of people killed in different parts of the island, which was omitted.

Continuing, Dr. Imray says:

"The country is ruined—irretrievably ruined. The island is devastated—absolutely laid waste from one end to the other, and I am afraid will never be able to rise from its ruins. The crop of sugar cane is totally destroyed; sugar works, proprietors' and negroes' houses leveled to the ground, and the provision grounds utterly ruined. The town has not suffered to as great an extent as the country, but still great damage has been done. More than a hundred people have been killed. The appearance of the country is altogether changed. Instead of being covered with verdure, it now looks as if fire had passed over it—scarcely a leaf to be seen. The trees left standing have quite the same appearance as in winter. The roads are completely impassable. Many estates are entirely ruined and must be abandoned. The negroes will be starving in a few weeks. The port has been opened for twelve months."

Unfortunately for our purpose, Dr. Imray's notes deal more with the destruction wrought by the storm than with the storm itself. It is hardly probable that any barometer, temperature, wind, or rainfall observations were made of the storm by anybody, and diligent inquiry has proved fruitless to obtain any further description of it.

Dr. H. A. Alford Nicholls, C. M. G., has kindly given the following very good description of the hurricane of 1883, including some reliable data from observations taken by himself during the storm. Although they may be of no value for the present purpose, they are forwarded as a matter of general interest, hoping they may be worth filing for future reference:

THE DOMINICA HURRICANE OF 1883.

"DOMINICA, *September 10, 1883.*

"During the afternoon of the 4th of September the sky was overcast, but there was nothing in the weather to excite suspicion that the island was to be devastated by one of the circular storms that sometimes occur at this season in these latitudes. Being much occupied, I did not, as is my custom, look at the barometer throughout the day, but I am informed on reliable authority that the mercury stood at 30.00 inches at 10 a. m., and this is about the usual height in ordinary weather. Toward evening rain set in, and it was raining heavily when I parted with your excellency at

10:30 p. m. On walking home I found the wind was blowing with some force from the northeast, and my suspicions became aroused as to possible danger.

"On reaching home at about 10:35 p. m., I examined the barometer carefully and found it to register nearly two-tenths below 30.00. The wind was now blowing in strong gusts from northeast by north, the rain was falling heavily, and the night looked very wild.

"I set to work at once to make my house secure, and, being thus occupied, I was unable to examine the barometer, again until 11 p. m., by which time the mercury had fallen to 29.764, and the storm had commenced to rage furiously, the wind coming with great velocity from the north-northeast. The barometer now fell rapidly; at 11:15 p. m. it registered 29.710, at 11:30 it stood at 29.598, and by midnight it was down to 29.362. It was now blowing a full hurricane from the north-northeast, and the noise occasioned by the rattling of the doors and windows and the crushing down of broken limbs of trees and debris of houses was terrific. At 12:30 a. m. on the 5th the height of the mercury was 29.212, and the wind blew, if anything, with increased force and velocity. The extraordinary atmospheric disturbance was plainly evidenced by the agitation and rapid descent of the column of mercury. Later on the wind fell. At 12:40 a. m. the barometer registered 29.026 and there was a dead calm, which lasted thirty-one minutes and which showed that the center of the storm was passing over us. At once I seized the opportunity of opening one of the doors of the house in order to look out on the night, and never shall I forget the scene that lay before me. To the north, close to the earth and apparently within a quarter of a mile of the town, was a large globular[1] mass of intense light, with forked lightning issuing from it in various directions; then, all at once, the whole ground appeared flooded with a sheet of lightning, which lasted sufficiently long to give one a glimpse of the destructive effects of the wind, The trees round about were wrecked, none but the larger branches remaining, and these bereft of leaves. There was no thunder, but the lightning came again and at short intervals, thereby showing the vast amount of electrical force present.

"At 12:45 a. m. the barometer stood at 29.010, and at 12:53 a. m. I read off 28.984, which was the lowest point reached. For a few minutes the mercury remained stationary, and then it commenced to rise gradually, and the wind set in from the south-southwest in gusts. The fastenings of one of my hurricane shutters now gave way, and, as there was much difficulty in securing it, I was unable to resume the observation of the barometer until 1:25 a. m., by which time the mercury had risen to 29.092; but the hurricane was still blowing in full force, and a shock of earthquake which then occurred made the howling of the winds to appear more terrific. The mercury now rose steadily and rapidly. By 1:49 a. m. it stood at 29.501, and by 2:03 a. m. it reached 29.588. At this hour I recorded in my notes that the wind came from the south-southwest "in fearful gusts," and every moment those in the house expected that the roof would have been blown off. Indeed, had the wind continued much longer with unabated fury most of the houses in the town must have been destroyed. By 2:15 a. m. there were frequent lulls in the wind and the mercury had risen to 29.672. By 2:34 a. m. it reached 29.752, and the wind began to abate, for the hurricane was passing away. At 2:53 the register shows 29.786, with the following note: "Wind falling, but occasional strong gusts." At 3:45 the mercury was up to 29.862, and there was no further danger. I was so exhausted with battling with doors and shutters, and with keeping an accurate record meanwhile, that I now fell asleep, and I regret to say that I have no barometrical reading until 5 a. m., when the mercury was at 29.972.

"I now opened the door and looked out on the country, and found the extent of the destruction astonishing. The day before the Roseau Valley and the surrounding hills looked lovely in the rich and magnificent clothing of tropical vegetation; now all vegetable life was blasted, and the scene was likened to a bleak winter morning in a northern clime. In my garden one large tree had disappeared. Another large one—I believe the largest silk cotton tree in the country—had branches as large round as a man's body torn off and thrown to a distance. But, strange to say, on the stone steps in front of the house stood my rain gage unbroken, and not even overturned. A child might have pushed the instrument off the steps with ease, for it was not secured in any way; but the hurricane had not shifted it an inch. Similar circumstances that have come under my notice led me to believe that the circular storm was composed of smaller circular storms, each with its central calm, for it seems impossible for me to account otherwise for the escape of flimsey houses while stronger structures within a stone's throw were utterly demolished. On seeing the rain gage intact, I measured the rainfall and found it to be 2.79 inches.

"I need not in this letter enter on a consideration of the destructive effects of the hurricane and the loss to life and property occasioned thereby, for as honorary secretary of the relief committee I have already placed your excellency in possession of all the particulars that have come to my knowledge.

"Before concluding, however, I may mention that the barometrical readings I have given may be considered to be scientifically accurate. They were read off from a Hick's standard barometer (No. 334) which was verified at the Kew Observatory less than two years ago. In the midst of the storm the instrument remained in an immovable position 60 feet above sea level close to one of the stone walls of my house, and during the night the average temperature, as read by the thermometer in contact with the barometer, was 85° F. The barometrical readings are uncorrected for elevation or temperature."

CHARLES E. ASHCROFT, JR., *Observer, Weather Bureau.*

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[1] This globular lightning rolled slowly down the Goodwill Ridge eastward to the sea.

The following notes relative to some of the most remarkable and destructive hurricanes of the West Indies, chronologically arranged, have been collected by Mr. W. H. Alexander, Observer, Weather Bureau, Basseterre, St. Kitts, W. I.:

1492—While coasting along the north coast of Cuba Columbus was driven by violent gales 56 leagues to the northeast. He was also compelled to remain in harbor off Espanola some days because of "stress of weather."

1493—On returning to Spain, Columbus and his fleet were overtaken by a severe storm which lasted three days and threatened them with certain destruction, so much so that Columbus wrote an account of his discoveries and threw it overboard.

1494—While on his second voyage Columbus anchored at Cape Santa Cruz, and while there "upon the 16th July a violent hurricane occasioned the admiral to declare that nothing but the service of God and the extension of the monarchy should induce him to expose himself to such dangers."

1498—When 480 miles southwest of the Cape Verde Islands, Columbus found that "the altitude of the north star was 5°." Here, in a calm, he expected that the heat would set the vessels on fire; the men were alarmed and dared not go below, though the stores were spoiling. This weather lasted eight days; the first only was clear, the seven following it rained; had all been as hot as the first, Columbus says, nothing could have saved them.

1502—While searching for a passage to the South Sea Columbus arrived off Santo Domingo, and asked permission to enter the harbor which was refused. His object in entering the harbor was to exchange his vessel and also for shelter from a hurricane which Columbus thought was approaching. The fleet sailed July 1, and within twenty-four hours 20 sail with all on board perished. Columbus said: "The gale was terrible, and in that night my vessels parted company, every one expecting death, and each considering it certain that the others were lost. With the exception of Job there never was a man who would not have died in despair. When to save my life and that of my son, brother, and friends, I was at such a time forbidden the harbors, which, by God's permission, I had gained for Spain, sweating blood. The vessel in which I was, weathered the gale marvelously; it pleased God that she received no damage whatever. My brother was in the unsafe vessel, and, next to God, was the means of saving her. In this gale we made Jamaica.

1508—On the 3d of August all the thatched houses in Santo Domingo, and several of those built with stone, every house in Bonaventura, and 20 sail of vessels, were destroyed by a hurricane. At first the gale blew from the north, then shifted suddenly to the south.

1509—On July 10 Admiral Don Diego Columbus arrived at Santo Domingo with his bride, and a few days later almost the entire city was destroyed by a hurricane. These visitations were considered marks of Divine displeasure.

1526—In October a violent hurricane did great damage in the Island of Espanola; rivers overflowed their banks. No such had been experienced in that island for many years.

1530—There was great distress among the inhabitants of San Juan because of a hurricane, which was followed by rain storms, so that the rivers were overflowed, crops, trees, and herds were washed away; the works at the gold mines and other undertakings were suspended.

1591—On July 17 a fleet of 77 sail left Havana for Spain and on August 10, in latitude 35° north, they were overtaken by a gale and the commander of the fleet with 500 men perished. Three or four days later, in another gale, 5 or 6 ships, with all their crews and the vice-admiral, were lost. About the end of August, in latitude 38°, they experienced another gale, during which 22 sail perished. September 6 the remaining 48 arrived within sight of Flores, where they were separated by another gale, so that of the 123 sail that were expected in Spain this year from the West Indies but 25 arrived.

1623—On September 19 a hurricane destroyed the tobacco crop on the Island of St. Christopher, this being the first crop planted and raised by the newly-arrived colonists.

1635—Du Pont, while on his way from Martinique to St. Kitts to bear the news of a treaty of peace between himself and the Caribs to D'Enambuc, was driven by a violent gale to the coast of Espanola, where he was taken prisoner by the Spaniards and closely confined for three years.

1642—During this year there were three hurricanes in the West Indies; the second lasted twenty-four hours, during which, at St. Kitts, 23 fully laden vessels were wrecked upon the coast, all the houses blown down, and the cotton and tobacco crops completely destroyed, and the salt ponds overflowed and rendered unproductive for some time.

1656—The Island of Guadeloupe was desolated by a fearful hurricane. Most of the houses were destroyed, all the domestic animals were killed, and all the plantations laid waste. Every vessel at anchor in the roads was wrecked and most of their crews drowned.

1664—The crop of potatoes was destroyed by a violent hurricane at Guadeloupe.

1666—On August 4 a hurricane began at Guadeloupe at 6 p. m., the wind blowing from the north. It continued with great violence until midnight when there was a calm of a quarter of an hour, the wind then shifting to the south and driving everything before it with irresistible force. Every vessel and boat on the coast of Guadeloupe was dashed to pieces, all the vessels in the Saints were driven on shore, and of Lord Willoughby's fleet (consisting of 17 sail with 2,000 troops) only two were ever heard of afterwards. An armee-en-flute of 22 guns got to Montserrat with only the stump of her mizzenmast standing, and a fire ship got to Antigua dismasted. The bottom of one ship was washed on shore at Capesterre, Guadeloupe, and another at the Saints; the whole coast was covered with wrecks of masts and yards; a figure from the stern of Lord Willoughby's ship was recognized among the ruins. The hurricane lasted 24 hours; houses and trees were blown down and a great number of cattle killed. The sea rose and was driven to an unusual height. All the batteries, walls of six feet thickness near the sea, were destroyed and guns, 14-pounders, were washed away. The storm was felt at St. Christopher and Martinique, but with less violence.

1667—September 1, a tremendous hurricane devastated the Island of St. Kitts; it began at 9 a. m. and lasted until 5 p. m. from the north, then shifting to the south, blew with such violence that all the houses and buildings were thrown down. The inhabitants sought shelter from its fury by throwing themselves upon the ground in the fields.

M. Laurent, the governor, in a letter to Mr. Colbert, says: "There has blown here the most violent hurricane ever known, and I hold myself obliged to inform you that this island is in the most deplorable state that can be imagined, and that the inhabitants could not have suffered a greater loss, or been more unfortunate, except they had been taken by the English. There is not a house or sugar works standing, and they can not hope to make any sugar for fifteen months to come. As for the manioc, which is the bread of the country, there is not one left, and they are more than a year in growing. I can not describe to you, sir, the misery of this poor island without wounding my heart. It is as a place over which fire has passed. I assure you that if peace is not made, or men of war sent into this country to facilitate the bringing of cassava from the other islands, that the inhabitants and troops will die of famine. I shall do everything in my power to keep up the spirits of the inhabitants, who are stunned like men that are totally ruined; and I shall not spare either pains or trouble to maintain the island and remedy the evil, which is irremediable except succor arrive from without."

1674—At Barbados, on the 10th of August, a hurricane blew down 300 houses, killing 200 persons, wrecked 8 ships in in the harbor, and so damaged the plantations that very little sugar was made the two succeeding years.

1675—The Island of Barbados was again devastated by a hurricane in August of this year. The crops were destroyed and the people asked the British Government to relieve them of an impost duty of 4½ per cent on exports. This was refused.

1681—The Island of Antigua was desolated by a tremendous hurricane.

The following account of two hurricanes which occurred at St. Kitts in 1681 is from a letter written soon afterwards and published in the first volume of A Young Squire of the Seventeenth Century. It seems so quaint and interesting that its reproduction verbatim et literatim is justified in this connection.

"Saturday the 27th of August, about one or two in the morning, the winds blew very hard at northeast, which did small damage. Before day, the weather broke up with appearance of fair weather; but before nine of the clocke, it was overcast and proved a rayney, blustering day. About eight or nine o'clock at night the wind, veering more to the north and from the north to the northwest, increased till midnight; at which tyme it blew so vehemently hard, and so continued with small rayne and frequent lightnings, until within less than an hour of daybreake (when the storm began to cease), that I had not a house standing upon my plantation, in which I could shelter myself from the weather.

"It was a little after midnight, when a great part of the roof of my dwelling-house began to fly away; several of my out-houses being allready downe. Then I thought it tyme to shift for myselfe; which I did. Turning my people out before (who had been driven to my house by the insufficiency of their houses) I locked the door, and tooke the key in my pocket.

"I could not goe against the winde; and with no small difficulty could I goe with it, for fear of being driven away by it. At last we got (all but one of our company) to a little hut, which, we had agreed upon before, to make our rendezvous in; which sheltered vs from the violence of the storme, but not of the raine, the thatch being partly blown away. But to be wet was then no news to vs. Wee were in continual feare oure little cottage should have beene blowne away; which rocked like a cradel. As soone as the storme began to cease, I went up to my house whiche I found miserably torne, and flat with the ground. My sugar-worke, in like manner, and all my buildings. I walked downe to my new sugar-worke, which I had built not long before, about a quarter of a mile or more from my house, towards the sea, to make my tenants' sugar canes; to whom I had leased fifty acres of land, and had newly begun to make sugar at it, and was then boiling at it, when the storme began. I found *that* likewise flatt with the grounde, the stone wall overturned, and the timber scattered in divers places farre distant from the house.

"I must confesse, I did wonder more to see my house standing, than to see what was destroyed, considering the impetuosity of the weather. I had scarce time to view this losse, when the winde being shifted into the south, the storme began afresh. I made what diligence I could (the pathes beeing all spoyled), to get to the place where my dwelling-house did stand; to whiche the winde assisted me, being in my back, but veering to the southeast.

"It blew a frett of winde, and continued with suche violence for severall hours, that it did much more damage in some partes of the island than the fore-part of the storme. But it was not comparable to the former with vs. I stoode for shelter behinde that part of the wall of my house, which was left standing, till I feared it would fall upon me, and then shifted to another shelter, little better than the former.

"About ten or eleven of the clocke, the winde ceased; but most part of the day was wet and rayney, very uncomfortable for those that had neither victuals to eat, dry cloathes to put on, or a house to shelter in, or fire to dry themselves by—which was the condition of most people. It was a deplorable sight to see the spoyle that was done in the canes and provisions, in comparison of which the losse of all our houses and workes is as nothing.

"That day, although Sunday, I got up a little house, in whiche to secure myselfe and the best of my goods from the wet; and I used all diligence to gett up a couple of rooms, and one of my sugar-workes, and to put some Indian provisions in the ground, having thirty-two negroes, besides whites to feed every day (for which I blesse God). I was now indifferently well at my ease for the present; my two rooms being built, and everything indifferently well in order, towards the repaireing of my buildings and my other losses. When on Tuesday, the fourthe of October, after a very tempestuous night, about breake of day, a second hurricane began, which lasted until two or three in the afternoone. I used all the endeavours I could to secure my new house, where I was lodged. But all my endeavours were not sufficient, but that, about ten or eleven of the clocke, the roof was blown away over our heads all at once and carried many yardes from the house—and *that* in a very instant of time. But I thank God none of vs were hurt, but one who had a small hurt with a nayle in a board.

"I made what haste I could out, and passed the remainder of the storme at the side of a wall, which afforded me some small shelter. This and the other hurricane were more fierce here and in another quarter, than in any other part of the island, as appeared by the effects of them. The damages done by this second storme, were very great, and would have been much more, had not the great spoyle wrought by the former hurricane deprived it of matter to worke upon. Though this was not so tedious, or exceedingly fierce as that, yet it hath destroyed our provisions, and hath occasioned a sickly and scarce time amongst vs. It was most violent at Antegoa, where several ships were cast on shoar."

1689—A dreadful mortality swept away one-half the inhabitants of Nevis.

1690—The Island of Antigua was almost desolated by an earthquake.

1692—Jamaica suffered from a dreadful earthquake on June 7 between 11 and 12 o'clock, noon. The town of Port Royal was almost completely destroyed in less than three minutes. About 3,000 of the inhabitants, with their houses, found one common grave. The sinking of the wharfs was but a prelude to that of the town. Those nearest the water first disappeared; and next in succession followed. In the meanwhile the streets began to gape, "opening those dreadful fissures into which the miserable remnant of the inhabitants fell, who had escaped the previous ruin, and were fleeing for shelter in the open air." The water began to roll where the town had flourished and swept from the sight the devastations which the earthquake had made. Several of the inhabitants were swallowed up and returned again to the surface of the earth through distant apertures which had no visible connection with those which first yawned to receive them. Some were returned alive and even without material injury. The waters rose and filled the houses, which had survived the shock, to the upper story, "a preternatural tide that was to ebb no more." Several of the streets were laid several fathoms deep under water; the harbor was agitated as in a storm. The ships parted their cables. The frigate *Swan* lay by the wharf and was forced over the tops of the sunken houses, and saved some hundreds of the inhabitants. The fort and about two hundred houses escaped; but part of the neck of land, about a quarter of a mile in length, was entirely submerged with all the houses, which stood very thick upon it. A general sickness ensued which, with the other miseries, left the island about destitute. The assembly ordered a perpetual anniversary fast in commemoration of this calamity.

1722—The town of Port Royal, Jamaica, was visited by a severe hurricane on the 28th of August, in which 26 merchant vessels were wrecked and 400 persons killed. An eye witness says: "The hurricane began at 8 in the morning, two days before the change of the moon; it gave at least forty-eight hours' notice by a noisy breaking of the waves upon the keys, very disproportioned to the breeze, a continual swell without reflux of the water; and the two nights preceding, prodigious lightning and thunder; which all the old experienced men foretold would be a hurricane, or that one had already happened at no great distance. The wind began in flurries from the northeast and flew quickly around to southeast and south-southeast, where it continued the stress of the storm, bringing such quantities of water that our little island was overflowed four feet at least; so that with the fierce driving of shingles about our ears, and the water floating boats, empty hogsheads, and lumber about the streets, those without doors were every moment in danger of being knocked on the head or carried away by the stream. Within it was worse; for the waters sapping the foundations gave continual and just apprehension of the houses falling, as in effect half of them did, and buried their inhabitants. * * * The whole rise of the water was computed at 16 or 18 feet at a place where it is not ordinarily observed to show above one or two. At 5 in the evening the waters abated, and so quickly as to leave the streets dry before 6. * * * Wrecks and drowned men were everywhere seen along shore; general complaints of loss on land which made it a melancholy scene, and to finish the misfortune, the slackness of the sea breeze, calms, lightning, stagnating waters, broods of insects thence, and a shock or two of earthquake that succeeded the hurricane, combined to spread a baneful influence, and brought on a contagion fatal for some months through the island.

B. Edwards says that as upon the same day of the month ten years before another hurricane had shaken the island the anniversary of the day was, by an act of the assembly, set apart for fasting and humiliation.

1737—On September 9 the town of St. Louis, Santo Domingo, was destroyed by a hurricane. All the sugar cane and cotton trees were destroyed and all the ships in the harbor were thrown upon the coast. This hurricane did great damage at St. Kitts and Montserrat. At the latter island it blew down all the windmills and houses and carried away mules, negroes, and cattle into the sea. The sugar canes were all destroyed.

1744—On the 20th October, at Jamaica, a dreadful hurricane began at 6 p. m. and lasted until 6 the next morning; the wind was all that time due south. Mosquito fort was demolished; eight English ships and vessels and 96 merchant vessels were stranded and foundered. Out of 105 vessels only one, the *Rippon*, rode out the gale, and she without masts. One hundred and eighty-two men were drowned.

1747—There were two violent hurricanes this year, one on September 21 and the other on October 24. They did great damage among the Leeward Islands. Fourteen sail were lost at St. Kitts and 36 at the other islands.

1754—A hurricane in September did great damage at Santo Domingo to the sugar and indigo plantations. Twelve ships were driven ashore and 1,700 hogsheads of sugar lost.

1759—"In the month of September of the year 1759 a heavy gale of wind from the northeast so greatly impeded the current of the Gulf Stream that the water forced, at the same time, in the Gulf of Mexico by the trade winds, rose to such a height that not only the Tortugas and other islands disappeared, but the highest trees were covered on the Peninsula of Larga, and at this time (so says Wm. Gerard de Brahm, Esq.), the *Litbury*, John Lorrain, master, being caught in the gale, came to an anchor, as the master supposed, in Hawke Channel, but to his great surprise found his vessel the next day high and dry on Elliotts Island and his anchor suspended in the boughs of a tree."

1761—On the 31st of March, at 4 p. m., the sea at Barbados began to flow; at 8 it appeared to ebb, but at 10 it increased considerably, and continued so until 6 the next morning. A similar agitation in the water was observed there at the time of the earthquake at Lisbon in 1755.

1762—A storm from the southward, followed by an earthquake, destroyed a great part of the walls surrounding the town of Carthagena on December 9; wrecked many houses, among them the castle of Santa Maria; drove two Spanish men-of-war on shore.

1766—This year seems to have been marked by an unusual number of direful calamities in the West Indies. An earthquake at Santiago de Cuba, killed 40 persons, and at Grenada the same or another threw down the sugar works and hills in several places, so that it was impossible to ride round the island on horseback.

At 10 p. m. of August 13 a strong northwest gale set in at Martinique, and about midnight the shock of an earthquake added to the horrors of the increased hurricane. At 3 a. m. the storm abated, and daylight revealed a scene of desolation and woe; wrecks and dead bodies covered the shore at St. Pierre; the streets were covered with ruins, while the roads were blocked by trees uprooted by the storm and enormous stones brought down by the rivers. At 5 a. m. a waterspout burst upon Mount Peleus, overwhelming the neighboring plains. By 6 o'clock it was quite calm and the sea was smooth. As many as 90 persons are said to have perished, many of these under the ruins of their own houses, while twice that number were wounded. Seven English and 28 French vessels were wrecked; also 12 passage canoes.

On the 13th, 14th, and 15th of September such violent gales raged at St. Kitts and Montserrat that 13 vessels were wrecked at the former and all at the latter. At Montserrat half the town was destroyed and upward of 200 persons reduced to distress by the torrent from the mountains.

St. Eustatius suffered severely from a hurricane on September 21; the provision grounds and cane plantations were destroyed; several vessels lost. The salt works at Tortuga were destroyed by the hurricane, also, and 3 French and 5 Newfoundland vessels driven on shore.

On the 6th of October 5 vessels were driven on shore at Dominica in a gale of wind, and upward of 50 sail at Guadeloupe.

On the 22d and 23d of October a violent hurricane did considerable damage in the harbor of Pensacola. The Spanish fleet from Vera Cruz for Havana and old Spain, consisting of 5 large ships of register richly laden, were driven ashore at the Bay of St. Bernard, 1768—On the 25th of October a brief but violent hurricane occurred at Havana. The storm began from the south and died away from the north, having continued not more than two hours; nevertheless, in that short time 96 public buildings and 4,048 houses were destroyed and about 1,000 persons killed almost instantly.

It was this year that the snow *Rodney*, carrying convicts to Maryland, was forced by stress of weather into Antigua. It is also stated that there was great distress among the convicts; as many as eleven died from want, and the survivors had to eat their shoes and the like to sustain life.

1770—On the 3d of June, in the afternoon, the Island of Santo Domingo suffered from a fearful earthquake. The City of Port au Prince was entirely destroyed; not one house was left standing, and more than 500 people were buried beneath the ruins. La Croix de Bouquet, a small town, with the greater part of the inhabitants was swallowed up. The sea rose a league and a half in the island.

1771—The great calamity of this year came in the form of a famine at the Bay of Honduras, caused, as it is said, by locusts. They ate up every green thing, and in some places covered the ground a foot thick. It is estimated that as many as 8,000 Indians died from starvation because of this awful visitation.

1772—During the last days of August and the first days of September a hurricane passed over the West Indies, causing frightful havoc among the Leeward Islands. At Dominica 18 vessels were driven ashore and lost. Several war ships were driven ashore at Antigua. At Montserrat and Nevis nearly every house was blown down. The hurricane passed over St. Kitts on August 31, beginning at daylight. At noon the storm abated to such an extent that the people thought that it was over, but the wind suddenly shifted from the northeast to the southwest by south, and blew with increased violence, destroying almost every house, sugar mill, tree, and plant, killing several and wounding many persons. The damage was estimated at £500,000 sterling. At St. Eustatius 400 houses were destroyed or rendered untenable, and the Dutch church blown into the sea. At Saba 180 houses were blown down. At St. Martins nearly all the houses and all the plantations were destroyed. The disastrous effects of this storm were felt nowhere more forcibly than at Santa Cruz, where, it is said, the sea rose 72 feet above its usual height, carrying every ship at the island on shore, some as far as 100 yards inland. Large stones were brought down from the mountains, and there was a terrific electrical display. Four hundred and sixty houses were thrown down at Christianstadt, and all but three at Fredericstadt. The magazines and stores were quite ruined. The total damage was estimated at $5,000,000. The damage at St. Thomas was placed at $200,000.

1779—This year was marked by a drought and famine at Antigua. The water supply became quite insufficient and the stock and negroes perished in the greatest agony. A malignant fever raged at the same time, threatening all with death. Mr. Baxter, a Methodist preacher, appointed the 28th day of May as a day of fasting, and he says: "It is remarkable that while we were assembled for prayer, the Lord granted our request by sending an abundance of rain."

1780—The hurricanes of this year were characterized by such unusual violence, and were attended by such appalling disasters that accounts of them may be found in many works on the subject, hence an extended account is not necessary in this place. As to the hurricane which swept over the Island of Jamaica, we reproduce the account given in Southey's West Indies, Vol. II, page 472.

"Upon the 3d of October the inhabitants at Savanna-la-Mar were gazing with astonishment at the sea swelling as it had never before; on a sudden, bursting through all bounds and surmounting all obstacles, it overwhelmed the town and swept everything away so completely upon its retreat as not to leave the smallest vestige of man, beast, or habitation behind. The sea flowed half a mile beyond its usual limits, and so sudden and unavoidable was the destruction, although it took place at noonday, that of the inhabitants of one gentleman's house, consisting of 2 whites and 40 negroes, not a soul escaped. Where the sea did not reach the destruction was nearly as effectual by the succeeding earthquake and hurricane; between both scarcely a house or building of any sort was left standing in the parishes we have named (Westmoreland and Hanover).

"The gale began from the southeast at 1 p. m.; at 4 it veered to the south and became a perfect tempest, which lasted in full force till near 8; it then abated. Forty of the inhabitants who had sought shelter in the courthouse were killed by the house falling upon them. At 10 there was a smart shock of an earthquake and the waters subsided. All the vessels in the bay were dashed to pieces or driven on shore."

We now come to the consideration of what is commonly and very properly called the great hurricane. A full history of this hurricane is not difficult to get and is worth the effort. In this connection we reproduce an account of this hurricane, found in a work entitled The Atmosphere, by Flammarion, beginning on page 377:

"The most terrible cyclone of modern times is probably that which occurred on October 10, 1780, which has been specially called the great hurricane, and which seems to have embodied all the horrible scenes that attend a phenomenon of this kind. Starting from Barbados, where trees and houses were all blown down, it engulfed an English fleet anchored before St. Lucia and then ravaged the whole of that island, where 6,000 persons were buried beneath the ruins. From thence it traveled to Martinique, overtook a French transport fleet and sunk 40 ships conveying 4,000 soldiers. 'The vessels *disappeared;*' such is the laconic language in which the governor reported the disaster. Farther north Santo Domingo, St. Vincent, St. Eustatius, and Porto

Rico were devastated, and most of the vessels that were sailing in the track of the cyclone were lost with all on board. Beyond Porto Rico the tempest turned northeast toward Bermuda, and though its violence gradually decreased it nevertheless sunk several English vessels. This hurricane was quite as destructive inland. Nine thousand persons perished in Martinique and 1,000 at St. Pierre, where not a single house was left standing, for the sea rose to a height of 25 feet and 150 houses that were built along the shore were engulfed. At Port Royal the cathedral, seven churches, and 1,400 houses were blown down; 1,600 sick and wounded were buried beneath the ruins of the hospital. At St. Eustatius 7 vessels were dashed to pieces on the rocks, and of the 19 which lifted their anchors and sailed to sea only one returned. At St. Lucia the strongest buildings were torn up from their foundations; a cannon was hurled a distance of more than 30 yards, and men as well as animals were lifted off their feet and carried several yards. The sea rose so high that it destroyed the fort and drove a vessel against the hospital with such force as to stave in the walls of that building. Of the 600 houses at Kingston, on the Island of St. Vincent, 14 alone remained intact, and the French frigate *Junon* was lost."

From the Gentleman's Magazine for 1780: "Alarming consequences were dreaded from the number of dead bodies which lay uninterred, and the quantity of fish the sea threw up, but these alarms soon subsided." (Compare this hurricane with that of 1666.—*A.*)

1781—On the 1st of August a gale of wind from the south at Jamaica sunk 2 loaded vessels and drove 24 others on shore, besides wrecking or driving on shore 73 light vessels.

1784—A hurricane began at Jamaica at 8:30 p. m., and continued up to 11 p. m. or later of July 30, sinking, dismasting, or driving on shore every vessel in the harbor except 4, causing the loss of numerous lives, The barracks were blown down killing 5 soldiers. The workhouse was destroyed and 10 of the inmates killed or wounded.

During the first three days of August the Island of Santo Domingo experienced a storm.

1785—A hurricane visited Jamaica on the 27th of August.

1786—The first storm of this year was in August, doing most damage at St. Eustatius where all the shipping was driven to sea and most of the small craft destroyed. It also swept the southern coast of Espanola. Another hurricane swept over Guadeloupe on September 10, doing much damage.

From Southey: "On Saturday, the 2d of September, an alarming hurricane threw the inhabitants of Barbados into the utmost consternation. At 11 p. m., when the storm was at its height, a meteor in the southeast issued from a dark cloud, and spreading its diverging rays to a vast circumference, continued, with unabated splendor, nearly forty minutes.

On the morning of the 3d Carlisle Bay was a scene of desolation, not a vessel had ridden out the storm. In the country great damage was done to houses and crops; many persons killed in the ruins of their own houses.

Jamaica came for her share this year on the 20th of October. The trees were stripped of their leaves and appeared as if fire had passed over them. The shores were covered with aquatic birds killed by being dashed against mangroves.

1787—According to the record there were three gales at Dominica this year, all in August; one on the 3d, one on the 23d, and one on the 29th. A number of houses, all the barracks, and all the vessels in the harbor were wrecked. In September, on the 23d, Balize experienced a severe hurricane, attended by heavy rains, and as the sea rose the land floods could not flow off, hence great damage was done by the overflow. It is stated that more than 500 houses were thrown down and 100 persons perished. Dead carcases and logs of mahogany were floating about in every direction. As many as 11 square-rigged vessels, besides the smaller ones, were totally lost.

1790—The little Island of Tobago is brought into notice this year by destruction wrought there in August by a hurricane, which, among other things, wrecked 20 vessels on the coast. As illustrative of the marvelous things sometimes performed by the hurricane we reproduce an account of what occurred on Mr. Hamilton's estate during this gale. "His new mansion, which had been built upon pillars, was lifted by the tempest and removed to some distance, but being well made did not go to pieces. Mrs. Hamilton, two ladies, and five children, were in the house and suffered little or no harm. Mr. Hamilton being absent from home knew not what had happened, but returning in the night, which was excessively dark, and groping for his door, fell over the rubbish left on the spot, and so far hurt himself that he was confined for a week."

1791—At daybreak, the 21st of June, it began to rain near Havana and contiued until 2:30 in the afternoon of the following day, with such force as to cause the greatest flood ever remembered in that country. The royal tobacco mills, and the village in which they stood, were washed away and 257 of the inhabitants killed. In the spot where the mills stood the water, or a partial earthquake opened the ground to the depth of 45 feet, and in one of the openings a river appeared of the purest water. Where the Count Baretto's house stood was a cavity more than 60 feet deep, from which a thick smoke arose. Four leagues from thence the torrent was so great that none of the inhabitants within its reach escaped. All the crops of corn and growing fruits were carried away. Three thousand persons and 11,700 head of cattle are said to have perished in the flood.—*Southey.*

1792—St. Kitts experienced a terrific flood which caused the loss of many lives and the destruction of much property. In August of this year a tremendous hurricane swept over the West Indies, causing great loss of life and property.

1793—About 30 vessels were lost or stranded by a hurricane in August at St. Kitts.

1803—On the 3d of September 13 vessels were wrecked by a hurricane. Among the vessels was the *Aurora* with cargo costing £46,000 sterling.

1807—The Bahama Islands were so desolated by hurricanes that the inhabitants suffered great hardships in procuring the necessaries of life.

1812—October 14, a hurricane devasted Trinidad, Cuba, wrecking 500 houses, and very much damaging the Pope's Convent and the hospitals, besides driving on shore or sinking many of the vessels in the harbor of Casilda.

1815—The West Indian Islands, especially the Leeward Islands, desolated by a hurricane which swept over them on August 31 and September 1. It is said that 30 sail were driven on shore at St. Bartholomew alone and 14 totally lost.

A hurricane on September 20 blew down or unroofed about half the houses in Turks Island, besides destroying about 400,000 bushels of salt. A number of vessels were wrecked, and one American vessel lost 22 of her crew and passengers.

On the 28th of October, Jamaica suffered very great damage from a hurricane. Several vessels with their crews were lost and others damaged.

1819—In September of this year a hurricane swept over the Leeward Islands, the Virgin Islands, and the Bahamas. It was first noticed near St. Lucia, passed over or near Antigua, St. Kitts, St. Barths, and St. Martins. It was most destructive in the Virgin Islands.

1825—On July 26 of this year a hurricane did very great damage to Guadeloupe. The Bishop of Guadeloupe was among the killed. It blew with considerable force at Dominica, Martinique, and Porto Rico.

1859—On September 2, a hurricane of rather mild form passed over St. Kitts, that is the center passed right over the island. It wrecked a number of boats besides other damage. It passed over St. Croix after leaving St. Kitts.

1871—A dreadful hurricane occurred this year in August. The center of the storm passed over St. Kitts. The barometer began to fall about 1 a. m. of the 31st, at which time the wind was from the east-northeast. By 6 a. m. the barometer had fallen to 29.60, and the wind had shifted to the north; at 8:40 the barometer stood at 28.50, and there was a calm lasting twenty-two minutes, after which the wind came from the southwest and the barometer began to rise. The damage done was quite general. The center passed right over Antigua and Statia also.

1876—In September of this year there occurred a severe storm. It passed to the north of St. Kitts on the 12th. The storm passed to the northwest at 7 p. m., and the lowest barometer reading recorded was 29.35. The wind shifted to west-northwest, west, west-southwest, southwest, and, finally, east-southeast. There was no thunder, but some lightning in the northwest and west-southwest at intervals.

1899—The great hurricane of this year was the one which occurred in August between the 7th and 14th. It was so violent and caused such widespread destruction that it will certainly be ranked as a historical hurricane, for which reason it is mentioned in this place. Entering the West Indian regions in the vicinity of Guadeloupe, it included in its majestic sweep the Leeward and Virgin islands, Porto Rico, and the Bahamas, not to mention the damage along the coast of the United States. The desolation and ruin wrought by this monster in the West Indies are fresh in the minds of all and need not be repeated here. Suffice it to say, then, that the wreckage along its path is comparable only to "the gambols of a bull in a china store." This hurricane was peculiar, in that it maintained a distinct organized existence for more than a month, finally dissipating in the region of the Mediterranean Sea.

In regard to the above notes on historical hurricanes it is not offered as a complete list of West Indian hurricanes, not even of *severe hurricanes;* but being forced to make selections for the sake of economy of space, the above were selected for reasons unnecessary to point out.

Most of the data are taken from Southey's Chronology, B. Edwards's West Indies, and Handbook of the Hurricane Season, by Westerly. The writer is also indebted to Dr. W. J. Branch, of Basseterre, St. Kitts, for data relative to the hurricanes of 1819, 1825, 1859, and 1871.

THE VIRGIN ISLANDS HURRICANE OF OCTOBER 29, 1867.

The following notes regarding this great storm are found in the Nautical Magazine, Vol. XXXVI, December, 1867:

It appears that the center of this hurricane, traveling in the usual west-northwest direction, passed immediately over the Virgin Group. On the 29th of October, at 11 a. m., at St. Thomas, the wind is reported as blowing a fearful hurricane from north-northwest half west, the wind all the morning having been from the northward. By 11 a. m., the wind at north-northwest half west, the barometer was down to 27.95. At 12:15 the wind had lulled, and at 12:30 it was almost calm, and at 12:40 it was almost dark. Shortly after, a most fearful rush of wind from south-southeast half east set in, and it continued to blow (how not said), but with gradually diminishing force, until 4 p. m. During this period a great deal of mischief was done. The storm appears to have traveled on an east-northeast and west-southwest line, the focus passing over Tortola and the harbor of St. Thomas, with the usual lull. The mention of two hurricanes is evidently by an inexperienced person, who seems to be quite uninformed on the principle of the rotary gales. In point of duration it was a mere transient gale (a day and a half or two days being not unusual with these hurricanes, while this lasted not half a day). However, the violence of it seems to have made up for its brevity.

It is estimated that upward of 600 persons were drowned at St. Thomas during the hurricane, the loss of life occurring mainly among the crews and passengers of vessels. Within forty-eight hours 300 bodies were washed ashore, recovered, and buried. The leading features of this calamity appear to be confined to the great loss of shipping and the destruction of houses in the islands of St. Thomas and Tortola. On shore many persons were killed by the falling of houses. Considerable damage was done along the shores of the harbors by the high seas, but the loss of life through the waves among the people on shore was very small. Amid the confusion of wrecks there was slight chance for identifying about eighty vessels which were known to have suffered more or less from the hurricane in the harbor. * * * After the hurricane had lasted some time there was a lull for about half an hour. It then recommenced with redoubled fury and lasted altogether three hours. The *Rhone* parted amidships and the waves ripped the gigantic steamer up just as if she were made of brown paper. * * * Seventy-five vessels were wrecked or seriously damaged; property to the amount of a million and a half or two millions pounds sterling was lost and about 500 persons perished. * * * All the islands appeared as if fire had passed over them. The town of St. Thomas looked exactly as if an explosion had taken place; roofs, doors, and windows having been blown away, and the streets were filled with tiles, trees, and rubbish. The harbor was filled with wrecks. * * * The hurricane occurred after the season was supposed to be over as the first full moon in October was on the 13th. * * * All the vessels that tried to go to sea were lost, with nearly all hands. * * * The wharfs which lined the shore were gone and every street was blocked up with broken rafters and debris of every conceivable description. Houses even were to be seen standing erect which had been lifted from their foundations many yards distant and dropped into some of the lanes running seaward out of the main street. A bombarded town could never have presented a worse picture of desolation and ruin. Plantations of whitened sticks covering the hills alone indicated that trees had at one time grown there. * * * The hurricane appears to have commenced at 12:10 and to have lasted with one break—at 1 o'clock, lasting thirteen minutes—till half past 3. The barometric indications of its coming were feeble until it had absolutely broken, then the downward progress of the mercury could be plainly seen. One or more shocks of earthquake were experienced, and in a moment the awful conflict had begun. At 1 o'clock the storm blowing from the northwest had ceased and the thirteen minutes lull took place. Again it broke forth with more dreadful energy from the opposite quarter and tore away many vessels which had until then rode securely. * * * The houses on the island appeared to have suffered more from the earthquake than the hurricane, destructive as the latter was. The particulars of the earthquake wave are so colored that it is difficult to arrive at the truth of them. An eyewitness stated that it swept directly over Brush Island, which is tolerably high, and advancing thence on the harbor was only prevented from visiting the town by the check it received from the overlapping points which in somewise shelter the entrance to the port. However, it appears pretty certain that vessels which were lying in four fathoms of water were left dry for a short time as the wave receded, but the subsidence must have been very gradual as none were wrecked from its effects, although at Santa Cruz an American frigate was deposited *in the market place*, where she was abandoned.

It is interesting to note that the almost completed negotiations for the purchase of the Danish West Indian Islands by the United States were ended closely following the occurrence of this hurricane and the earthquake of November 18.

SAN JUAN, PORTO RICO.

Porto Rico has been devastated by many hurricanes, but the records beyond the mere statement of the facts, are very incomplete and inaccessible. Four, however, stand out prominently as having committed terrible ravages. These are the hurricanes of Santa Ana on July 26, 1825; Los Angeles on August 2, 1837; San Narciso on October 29, 1867; and San Ciriaco on August 8, 1899.

Owing to the paucity of records it is almost impossible to say which of these four was the most severe, but it is the generally conceived opinion that that of the Los Angeles was the worst. There being no meteorological data available, however, it can probably be said that the hurricane of San Ciriaco was very nearly as severe as regards the velocity of the wind, and very much more so as regards the destruction of property and life. This is probably due to the fact that in 1837 the population of the island and the number of buildings was very much less. The latter hurricane having also occurred while a station was in operation in San Juan, we are enabled to present meteorological data which is entirely wanting in the former.

The rainfall during San Ciriaco was excessive, as much as 23 inches falling at Adjuntas during the course of twenty-four hours. This caused severe inundations of rivers with which Porto Rico is so liberally endowed, and the deaths from drowning numbered 2,569, as compared with 800 killed by injuries received from the effects of the wind. This number does not include the thousands who have since died from starvation. The total loss of property was 35,889,013 pesos (dollars).

For several days previous to the hurricane the meteorological conditions had been peculiar. On the 3d calm was recorded at both the morning and the evening observations. Between midnight of the 3d and 8 a. m. of the 4th but 4 miles of wind were recorded. The barometer showed no rise such is usually anticipated immediately preceding a hurricane, the mean of the 5th being 29.96, and that of the 6th 29.98. During the afternoon of the 7th the sky was unusually hazy, and the lower clouds were moving rapidly from the northeast. About 3 p. m. the sky was covered with thick alto-stratus and stratus clouds, the former moving from the southeast and the latter from east-northeast. At this time the barometer registered 29.865. At 10 p. m. the barometer began its downward movement, which did not cease until the lowest reading, 29.23 inches was reached, at 8:30 a. m. of the 8th, at which time the mercury in the tube was oscillating violently.

The storm passed to the south of San Juan, and striking the island on the southeastern part, passed in a direction north of west until it passed the northwestern part, the time consumed in its passage being from 7:00 a. m. until 1 p. m. The wind reached no very high velocity until 2 a. m. of the 8th. At 10 p. m. of the 7th, however, it came in puffs, some of them of considerable violence. At 5 a. m. of the 8th it was raining and blowing furiously, both increasing until between 7 and 9 a. m. the hurricane was at its height, the wind reaching a registered velocity of 66 miles an hour from the northeast. The wind shifted during the progress of the hurricane from northeast to southeast.

There was noted in the case of this hurricane, as has been noted in subsequent ones, a decided lowering of the relative humidity immediately preceding.

The total loss of life caused by this hurricane was 800, and 2,569 persons were drowned.

R. M. Geddings,
Section Director, Weather Bureau.

THE "PADRE RUIZ" HURRICANE, SANTO DOMINGO, W. I., SEPTEMBER 23, 1834.

The most severe and destructive hurricane on record that passed over this city is the one generally known as the "Padre Ruiz" storm, which occurred on September 23.

It derived its name from the fact that it began when the funeral services were being held over the body of the priest of that name in the church of Santa Barbara.

The loss of life and property was appalling. Everything was laid waste before its fury. Large tracts of timber on both sides of the Ozama River were torn up by the roots; many vessels were lost, and the suffering of the people was something terrible. Hundreds of houses in the city were unroofed or blown down and many lives and thousands of head of all kind of stock were lost.

The stone church at San Antonio was unroofed and then demolished. Its ruins are still standing as a monument of the fury of the storm. The downpour of rain was so great that a fisherman by the name of Jose Ramon was drowned in the principal market space of the city, as no one dared to go out on the street to render him assistance.

(Translated from Historia de Santo Domingo.)

Louis Dorman,
Observer, Weather Bureau, Santo Domingo, W. I.

JAMAICA, W. I.

Vol. 11 of the Jamaica Weather Reports, by Mr. Maxwell Hall, Government Meteorologist, contains the following descriptions of noteworthy hurricanes which have visited that island:

August 28, 1722.—This great hurricane damaged the whole island; the center passed over Port Royal, where the water rose 16 feet above its usual level. "It began at Port Royal," writes Long (Vol. 11, p. 145), "at 8 in the morning, and lasted fourteen hours, during which time the rain was incessant and the storm veered all around the compass. In Kingston most of the buildings were thrown down or much shattered. The day preceding was perfectly calm, but so great a swell at sea that the waves broke over the breastwork at Port Royal and laid all the streets under water. The fort suffered very much; several guns were dismounted and some washed into the sea. The church and row of houses in the east part of the town were so battered that there remained very little appearance of buildings. In short, about half the town was laid in ruins, and the houses and plantations in all parts of the island suffered considerable damage, except in St. Jago, where the Spanish buildings stood the shock unhurt. Very few of the inhabitants lost their lives, but in the harbor it proved more fatal." Part of the squadron was at sea, but out of 50 vessels in port only 4 men-of-war and 2 traders were saved, with the loss of their masts. About 400 lives were lost. After the hurricane there was a calm, and the air was poisoned by the smell of decaying bodies, and an epidemic broke out.

October 20, 1743.—"Another furious hurricane," writes Long, "arose at 6 in the evening (at Port Royal) and continued until 6 the following morning. A new fort begun at Mosquito Point (Fort Augusta) was entirely razed; many houses were blown down in the towns and other parts of the island, and all the wharfs at Port Royal, Kingston, Passage Fort, and Old Harbor were destroyed and most of the goods swept away. The inhabitants of Port Royal expected every moment to be swallowed up by the inundation, the streets being all laid several feet under water; but, happily, their wall withstood the shock and saved them from utter ruin. Their dangerous situation may be imagined, for the wind, setting the whole time from the south, drove the surge full against this part of the town with such fury that immense loads of stone and sand were poured over the wall. Sir Chaloner Ogle, who then had command of this station, was fortunately at sea with the major part of the fleet; but there were 9 men-of-war and 96 merchant ships in harbor, 104 of which were stranded, wrecked, or foundered, so that only the *Ripon* rode it out, with the loss of her masts, and a great number of marines were drowned." A pestilence followed, which proved fatal to a still greater number of lives.

WILLEMSTAD, CURACAO, WEST INDIES.

Leon J. Guthrie, Observer, Weather Bureau, submits the following regarding Curaçao's most severe storm:

The hurricane of September 23, 1877, is the only destructive storm on record here. As no records were kept by the government at that time it is impossible to obtain entirely reliable data, therefore the report is confined to desultory observations by sea captains and private individuals and to extracts from consular reports and newspaper files.

The day preceding the storm was unusually calm, with light gusts of wind. From 4 a. m. until midnight the pressure remained stationary at about 29.80. Shortly after noon a few swiftly-moving cirrus clouds were observed but their direction was not remembered. Early in the afternoon the sky became overcast, presenting a dark greyish color, and the sea swell was long and increasing in height. During the evening the wind increased to almost a gale from the northeast and dark, heavy clouds formed along the eastern horizon. The barometer read 29.80 at 4 a. m., 8 a. m., 2 p. m., and midnight, but began to fall shortly after midnight—slowly until 3 a. m., then more rapidly. Light drizzling rain fell at intervals during the afternoon. After midnight the wind increased steadily from the northeast and the swell was very heavy. Heavy rain began about 3 a. m., and the pressure at that time was 29.75, a fall of but .05 in three hours. At 5 a. m. a tremendous sea was running; the wind changed to north, increasing to hurricane velocity, and rain fell in torrents. From 5 to 9 a. m. the storm increased in violence, reaching its maximum strength about 8 a. m., when "In the city proper many houses were totally destroyed, and many others partially, both by the force of the wind and by the waves which rolled inward from the sea, washing the most substantially built houses away as if they were built of paper" (extract from United States consular report). The pressure continued to fall until 11 a. m., when it began to rise; the wind changed to east, but continued to blow with great violence. At 2 p. m. the wind changed to southeast, becoming considerably lighter. The barometer had risen rapidly and by 4 p. m. the weather cleared, the wind and waves had greatly diminished in force, and the storm had passed.

There were no temperature readings taken, and the only barometer readings were taken by some private person and published in the Curaçao Courant. They were as follows: September 22, 4 a. m., 29.80; 8 a. m., 29.80; 2 p. m., 29.80; midnight, 29.80. September 23, 3 a. m., 29.75; 5 a. m., 29.70; 9 a. m., 29.60; 9:30 a. m., 29.55; 10:30 a. m., 29.45; 11 a. m., 29.45; 11:45 a. m., 29.50.

It is generally believed that the center of the storm passed some distance south of Curaçao, moving from southeast to northwest. The captain of a small sailing vessel reported a barometer reading of 29.20 at some distance south of the island. The lowest recorded reading on the island was 29.45.

The number of lives lost was never known, but it is thought that it was no more than 16. The damage to property approached $800,000.

SANTIAGO, CUBA, W. I., *April* 10, 1900.

Mr. Mason, British Consul at this place, has given me a statement which I inclose herewith. Mr. Mason informs me that he was appointed a Voluntary Observer for the United States Signal Corps in 1878, and reported the storm he refers to in his statement.

"Since the year 1866 I know of no very violent storm striking this vicinity. The first storm which I saw was in 1878, and since then I have seen three more, including that of last year, which have caused some damage in this vicinity, but the damage has been chiefly caused by excessive rain, even to the buildings in town, many of them being built of cujes or adobe.

"When I came here I frequently heard reference to a severe hurricane felt in the early fifties, I think in 1852 and in August, but I have not been able to find any data.

"On the other hand, from one or two quite old gentlemen, I have gotten some particulars of a severe hurricane which did much damage in this vicinity in the year 1831. One of them says it occurred on Saturday, the 13th of August, that he was living in the country about thirteen miles from Santiago, and can remember that the wind began to blow quite gently about 7 a. m., but by 9 a. m. it was blowing hard, and that it blew from all directions until 5 p. m., when it began to abate; that it blew so hard that they could not go out of the houses, and that it was impossible to pass along the road. He remembers that branches of trees flew through the air like feathers, that all rivers overflowed and could not be crossed for four or five days; also that the roads were completely spoiled."

I see in Miguel Roderigues Ferrer's book that he cites Poey and others as describing a hurricane in that year.

I have so far been unable to find here any printed data with regard to any hurricane.

A. V. RANDALL, *Observer Weather Bureau.*

PUERTO PRINCIPE, CUBA.

From the fact that details are meager and stories conflicting, it is evident that, for a good many years, no storm great enough to impress itself upon the memories of the people, has visited this place.

The most reliable source of information tells us of three storms whose accompanying phenomena have been noticeable here. One of these passed south of Santa Cruz in 1878; the one which most nearly approached this place passed through Santa Cruz in 1894, while the third one referred to passed north of the island in 1895.

The storm of 1894 was accompanied by high winds and heavy rains, which raised the Hatibanico River to the greatest height recorded. Very little damage was done, and it is believed that no lives were lost. Other details are conflicting, even contradictory, and there seems to be a controversy regarding the exact date.

PAUL DEGRAW, *Observer, Weather Bureau.*

CIENFUEGOS, CUBA.

During the latter part of the year 1825 the Colony of Cienfuegos, which had been founded about six years before, was almost completely destroyed by a severe hurricane, only three or four houses being left standing. A subscription was made throughout the island large enough to restore to each homeless colonist the value of one-third part of what he had lost. Apparently these first houses had been little better than huts, as the historian states that those built after the storm were of a more substantial character, some being of wood and others of masonry.

On October 13, 1877, the influence of a hurricane began to be felt in Cienfuegos. The barometer reached its minimum, 744.7 mm., during the 18th and 19th, and oscillated between 745 and 746 mm. for twelve hours, during which period the vortex of the storm being to the west of the city, very high and steady winds were experienced from the southeast, south-southeast, and south, a maximum velocity of 72 miles per hour being attained. The water in the harbor rose 4 feet above its ordinary level, flooding many streets in the lower part of the city, and also the houses, so that the dwellers therein had to abandon them, some families being rescued in boats by the police, firemen, and others. The high houses especially suffered from the wind, and the wharfs were much damaged by the sea. Many vessels in the harbor were dragged from their anchorage, and some were wrecked outside the harbor, one, an English bark, the *M. E. Chapman*, while trying to enter. No loss of life is mentioned, but it was found necessary to issue rations to many of the poor who had lost their homes, and on the 22d more than 1,000 people visited the mayor's office to solicit food.

The approach of the hurricane of 1882 was first indicated in Cienfuegos on the 4th of September by a falling barometer. Little notice was taken of this, however, as it was unusual for this section to be visited by hurricanes at this season of the year. At 11 p. m. of the 4th the barometer marked 760 mm.; the sky was threatening and there was much heat. The pressure continued decreasing slowly to 758 mm. at 4 a. m. of September 5, with showers and light gusts of wind from the north-northwest. The wind increased in strength. At 7 a. m. the barometer stood at 756 mm., and at 9 a. m. at 752 mm., with occasional violent gusts of wind from the northwest. After this latter hour the barometer fell rapidly, the gusts of wind and the rain increasing, until at 11 a. m. the barometer marked 742 mm., with furious gusts of wind from the west, which did not cease until 1 p. m., and destroyed whatever was in their path. The barometer reached its minimum, 741 mm., at 12 noon amid a general tumult of elements. At 12:30 p. m. it marked

741.10 mm., the wind backing toward south-southwest, but still blowing very heavily. At 1 p. m. the wind was southwest, with barometer 742 mm.; at 1:15, 743 mm., with heavy gusts from the south-southwest; at 1:30 p. m., 744 mm., and at 1:45 p. m., 745 mm. From 2 to 3 p. m. the wind was backing to the south, and the pressure increased to 748 mm. At the latter hour the gusts from the south increased in force and continued until 4:30 p. m., with the barometer rising slowly. After 5 p. m. the wind began to die down, although rain still fell abundantly. At 9 p. m. the barometer had risen to 756 mm.

This hurricane, of a diameter of more than 100 leagues, and whose vortex cut the meridian of Cienfuegos at noon of September 5, from 5 to 9 leagues north of the city, caused great damage and loss throughout this section. One boy was drowned and many persons suffered slight injuries. There was scarcely a house in the city that was not more or less damaged. Some were broken down completely, while parts of the roofs and walls of others were blown to the ground. The signal staff belonging to the captain of the port was blown down. The gas plant was partially wrecked. Nearly all the trees in the city, except the palms of the Plaza de Armas, were uprooted. All of the wharfs suffered considerable damage. In some of the small surrounding towns nearly all of the dwelling houses were destroyed. The vortex of the storm appeared to pass directly over Cartagena (a small village 15 to 20 miles to the north) and at that point scarcely a house or tree was left standing. Crops of all kinds throughout this section also were greatly damaged.

Mr. J. S. Murray, an American civil engineer, who was living in this city at the time of the hurricane of 1882, states that a wind gage at Central San Lino, a sugar plantation some miles to the north of Cienfuegos, recorded a maximum velocity of 92 miles from a westerly direction; also that all but one of the vessels in the harbor here were blown ashore.

In the summer of 1888 another severe hurricane passed near this city and caused much damage. During the passage of this storm Mr. Murray took a number of barometric readings and notes, which he has offered to furnish me copies of, but up to this time he has not succeeded in obtaining them for me.

JAMES L. BARTLETT, *Observer, Weather Bureau.*

HAVANA, CUBA.

Years in which hurricanes occurred on the Island of Cuba; also monthly date of occurrence; and lowest barometer reading, when given.—*Marcos T. Melero, Diario de la Marina, October 9, 1873.*

1494. May 19-20.
1498. Hurricane which damaged the naval fleet of Spanish Admiral Colon, en route from Cuba to Spain.
1527. Hurricane which destroyed the naval fleet of Spanish Admiral Panfilo Narvaez, in Casilda Harbor.
1557. A furious hurricane throughout the island.
1588. A furious hurricane; more destructive than that of 1557.
1679. February 11.
1692. October 24. Storm of San Rafael, in Havana.
1712. October. Storm in Havana.
1714. Strong hurricane throughout the island.
1730. Storm in Havana which destroyed the Paula Hospital.
1733. Strong storm throughout the island.
1744. November. Storm; after which a plague of worms appeared among the cattle.
1755. November 1. Storm; through which the city was inundated by the waters of the Gulf of Mexico.
1756. October 2 and 3.
1766. June 11.
1768. October 15.
1778. October 28.
1780. October 17.
1784. March 8. Strong storm, attended with hail; named "Storm of San Juan de Dios."
1791. June 21-22. The river Las Puentes overflowed, inundating the country as far as Cerro.
1792. October 29.
1794. August 27-28.
1796. October 3.
1796. October 24.
1799. Storm on the southern coast.
1800. October 14-15.
1800. November 2. Hurricane in Santiago de Cuba, with rain and earthquake.
1807. September 5. Lowest barometer, 29.79.
1810. May.
1810. June.
1810. September 28.

1810. October 24-25. Lowest barometer, 29.35. Storm in Vuelta-Abajo, Pinar del Rio Province, called the "Salty storm."
1812. October 14. Big storm in Trinidad, Cuba.
1819. Big hurricane over the southern coast.
1821. Big storm in Havana. Lowest barometer, 29.31.
1825. October 1. Hurricane in Trinidad and Cienfuegos.
1826. Hurricane throughout the island.
1831. August.
1832. Big storm throughout the island.
1833. October. Big storm in Vuelta-Abajo, Pinar del Rio Province.
1835. August.
1837. July 26. Big storm in Trinidad.
1837. October 25 to 26. Lowest barometer, 28.06.
1841. November 28. Lowest barometer, 29.55. Storm in Havana, called the "Mercurial storm."
1842. September 4. Lowest barometer, 28.93.
1844. October 4 to 5. Lowest barometer, 28.84.
1846. October 10 to 11. Lowest barometer, 27.06.
1850. August 21-22. Lowest barometer, 29.52 to 29.37.
1856. August 27. Lowest barometer, 28.62.
1859. October 2.
1865. October 22. Barometer 29.00; lowest barometer, 28.78.
1870. October 7-8. Lowest barometer, 29.38.
1870. October 19-20. Lowest barometer, 29.32.
1873. October 6. Lowest barometer, 29.56.

HURRICANES AT HAVANA OF WHICH DATA ARE OBTAINABLE.

1. *October 15, 1768.*—Wind of hurricane force blew for a little more than one hour from the southeast, backed to northeast, and later to northwest. The maximum force of this hurricane was experienced from the northeast and north; the wind decreased and weather cleared when the wind backed to northwest.

The damage to vessels in the harbor was as follows: Blown on the beach and their hulls, masts, and rigging injured: (Men-of-war) 2 line-of-battle ships, 3 frigates, 5 schooners, 5 sloops, and 1 pontoon; (merchant vessels) 10 frigates, 2 barks, 5 packet boats, 5 sloops, 5 settees (lanteen-sailed boats), and many of the small boats that ply the harbor.

2. Occurred during six hours of the night of the 27th and 28th of October, 1794. The hurricane began with southeasterly winds, then they backed to the northeast, from which direction the maximum wind force was experienced; then backed to the northwest, when the wind diminished and the weather cleared.

Considerable damage was done to shipping in the harbor and to the wharfs. The following vessels were blown on shore: (Men-of-war) 1 line-of-battle ship, 1 frigate, 1 brigantine, 2 sloops, 1 schooner, and 6 small boats belonging to the arsenal; (merchant vessels) 7 frigates, 7 brigantines, 8 sloops, and 42 schooners; besides these, all the small harbor boats were either totally destroyed or so severely damaged as to require very great repairs.

3. Occurred during three hours of the night of October 2-3, 1796. The hurricane began with east-northeast winds, which backed to north, and later to northwest, when winds began to decrease in force and the weather to clear.

The following vessels were lost: 1 brigantine and 2 schooners of the Spanish Navy and 1 brigantine of the American Navy. The following were blown on shore and injured: 1 bark and 2 brigantines of the Spanish Navy and 2 brigantines of the American Navy, also 6 schooners of the Spanish merchant marine. Some cables (ship?) were broken and other minor damage done.

4. Occurred on September 4, 1842. At the break of day the wind began to blow very strongly from the northeast and increased in force until 2 p. m.; it was of great violence, attended with heavy rains. At 4 p. m. the wind backed to northwest and continued to blow with great violence until 10 p. m., after which hour it began to diminish in force. The loss caused by this hurricane was some damage to buildings, inundation on Animas and Trocadero streets, the washing away of boilers by the waves at the Punta, and great damage to crops and trees in the country.

5. Began with a southeast wind at 6 p. m. of October 4, 1844; backed to northeast and north and continued with hurricane force until 9 a. m. of the 5th, the hurricane attaining its maximum force at daybreak; after 9 a. m. the winds backed to northwest and decreased in force.

All the vessels of the navy (number not given) in the harbor were damaged in hull, masts, and rigging, and the schooner *Ligera* was carried away from her moorings by the steamer *Congress*, which was being blown toward the arsenal. The following coasting vessels were blown on the shore: 76 schooners, 1 steamer, 2 sloops, 10 lighters, 8 supply boats, and many of the smaller harbor boats. Of the vessels of the seagoing merchant marine 4 brigantines were blown on shore, others lost their masts, and many were severely damaged.

In Havana many doors and windows were blown out, and all the trees in the city were blown down. In the territory between the meridians of Havana and Cardenas all of the villages were almost totally demolished, and the plantations destroyed.

The following information regarding this hurricane was received from the various sources quoted below:

Mail boat *No. 3* sailed from Havana on October 4, 1844. At 6 a. m. of the 5th very violent winds were blowing; at 1:30 p. m. the wind backed to west-northwest, and blew with hurricane velocity; at 4:30 p. m. the wind veered to northwest and weather cleared.

Batabano, October 2, 1844.—Northerly winds began to increase in force, and by the 3d they had attained the intensity of a hurricane. The winds decreased on the afternoon of the 5th. Some ships were lost at sea and some blown on shore and wrecked; one vessel was carried by the waves one-half mile inland, and left there when the water receded.

Matanzas, October 6, 1844.—Yesterday, the 5th, was a day of horror and destruction. A terrific hurricane, which lasted eighteen hours, destroyed the majority of the wooden warehouses along the river banks, and the rivers overflowed, destroying everything in their paths. The Yumuri River for six hours inundated the territory as far inland as the printing office of the Aurora, seven blocks from its banks, and families in this district were driven from their houses and forced to seek shelter and safety elsewhere; many had to wade through water waist-high. The San Juan River overflowed and inundated the territory as far as the Pueblo Nuevo, and then flowed along the roadway. It is impossible to estimate the loss suffered by Matanzas, as not a single house has escaped injury. It is believed that between 4,000 and 5,000 boxes of sugar have been lost. Of the 15 or 20 vessels in the harbor only one could ride to its anchors; the others were blown against the wharfs. It is thought that the steamer *Cardenas* has been damaged beyond repair.

It is learned that Aguacate, Madruga, and Lazuna de Palos suffered as severely as Matanzas by the ravages of the hurricane. Alquizor also suffered very greatly, and there is not a single tree standing in that territory, excepting the palms. From Tapaste and Madruga reports are received to the effect that not a single house remains on the coffee plantations, and the coffee trees have been greatly injured.

6. *Hurricane of October 10-11, 1846.*—On October 10 the barometer fell rapidly from 10 a. m. to 4 p. m. At 10 a. m. the barometer read 29.68 and the thermometer 80°, and at noon barometer read 29.50 and thermometer 80°. The wind blew very strong from the northeast, with frequent rain squalls. At 4 a. m., October 11, the barometer read 29.24, and thermometer 80°; the wind blew with hurricane velocity from northeast and north, attended with excessively heavy showers of rain. At 6 a. m. barometer read 29.14, thermometer 80°, with furious northeast to northwest winds blowing; at 9 a. m. barometer read 28.50, thermometer 79°. The wind continued blowing with hurricane force until 10:30 a. m., when it reached its maximum velocity from the north, at which time (10:30 a. m.) the barometer read 27.74 and thermometer 79.5°. At 11 a. m. the wind was steady from the west-northwest, attended with heavy rain squalls, and a tendency to rising barometer. At 12 noon the barometer read 28.35 and thermometer 79.5°; wind very strong from the northwest and west-northwest, with frequent rain squalls. At 2 p. m. the barometer had risen to 28.91, and heavy and frequent rain squalls from the west-northwest and west had occurred. At 4 p. m. the barometer read 29.23 and thermometer 80°; the wind continued to blow very strong, but the rain squalls were becoming less frequent and with decreased rainfall. At 5 p. m. the barometer read 29.30 and thermometer 80°.

Very great damage was done to buildings throughout the city, and several lives were lost. The roof of the principal theater was blown off, the front wall was blown down, and the building presents the appearance of a pile of rubbish. Many families were compelled to abandon their houses and seek shelter in more secure places. The roof of the Cathedral was in a very bad condition; the cupola of the Sacrista Chapel was blown down and the upper windows blown out. The upper story of the Seminary College was rendered uninhabitable and most of the partitions on the second and third floors collapsed. The tower and a part of Angel Church building were blown down. The roof of Montserrate Church was blown off and the doors and windows blown out. The parish churches of Jesus del Monte and Guanabacoa were ruined. All the buildings of the tannery belonging to Señor Xifre were greatly damaged and one negro killed. The Liceo Building was greatly damaged and all the doors and windows were blown out. The gas plant was seriously damaged by the blowing down of the big smokestack of the factory; a big stone turret was blown over on the roof of the secretary's office and broke in the roof of the office. The railway station suffered great damage. In Havana Harbor the damage was greater than that caused by the hurricane of 1844, and many vessels were wrecked and blown on shore.

Matanzas, Cuba, October 10, 1846.—After having blown very fresh from the east-northeast, the wind diminished somewhat, but the weather remained dark and drizzly; barometer read 29.80 (time not given). At 9 p. m. the wind began to increase in force and the barometer to fall. At 11 p. m. the wind still continued to increase, with heavy gusts, until 4 a. m. of the 11th, when wind veered to southeast and blew with the velocity of a severe hurricane, carrying the steamer *Cardenas* from its moorings. At daybreak on the 11th the harbor presented a sad prospect, being covered throughout by wrecks, some blown on shore and others sunk in the harbor. At 6 a. m. the wind backed to east-southeast and diminished somewhat in force, but occasional strong gusts continued until 10 a. m., at which time barometer read 29.30 and wind veered to south and south-southeast and again increased and became of great violence, and so continued; at 1 p. m. the barometer read 29.80. The wind began to decrease at 2 p. m.—but rain squalls continued—and veered to south-southwest, and continued to decrease until 4 p. m., when it veered to southwest and became calm.

Of all the vessels in the harbor only the American frigate *Ranger* and the coastwise schooner *Antonia* held to their anchors, 10 vessels in the over-sea trade and 25 vessels in the coasting trade being either very severely damaged or entirely lost. This hurricane also caused the loss of many lives and destruction of, or damage to, much property. Many houses, both in the city and country, were destroyed, together with all crops, and a great number of trees; railway cars were blown over, and many heavy ox carts were carried by the wind several yards from where they stood.

On the plantation Alejandro, Guines, the negroes had taken shelter in the owner's house. The house was blown down, killing many of the negroes, 56 bodies having been recovered from the ruins up to noon of the 11th. A later dispatch, dated the 15th, reported the number of bodies recovered from the ruins of the plantation house as 84.

On the plantation Providencia, in the same locality, only a very few of the negroes escaped death. Number not given.

It was thought that the number of deaths in Guines amounted to 100.

At Cardenas the hurricane was not so severe as at Havana and Matanzas.

7. *August 21-22, 1850.*—From 4:30 p. m. of August 21, 1850, the winds were variable, shifting between northeast and northwest. At midnight they shifted to southwest and increased in intensity, and from 7 to 10 a. m., August 22, they were of great force, diminishing after 10 a. m. At 6 a. m., August 22, the barometer read 29.37 and the temperature 80°.

Crops were destroyed and many trees blown down. At the gas house the roofs of two houses were blown off, and a man who exposed himself to the wind was knocked down. The rivers overflowed, causing an extraordinary inundation, and some wooden houses were destroyed.

8. *August 27, 1856.*—At 8.54 p. m. on August 27 the barometer read 29.70; at 9.05 p. m., 29.57; at 9.25 p. m., 29.52; at 9.45 p. m., 29.49; remained at that height until 12 midnight, after which hour it began to rise.

9. *October 22-23, 1865.*—At 4 p. m., October 22, the barometer read 29.39, wind, east; at 8 p. m., 28.96, east-southeast; at 9 p. m., 28.81, south; at 10 p. m., 28.79, south-southwest; 10:30 p. m., after a period of calm, the wind again increased and blew very strong; 12 midnight, 29.05, wind west-southwest, and beginning to diminish in force. At 5 a. m., October 23, the barometer read 29.80, wind west.

Of the vessels at the Caballeria wharf 30 or 40 were destroyed, with their cargoes, and many others greatly injured. Most of these vessels were lighters loaded with assorted merchandise, sugar, etc. Some houses were damaged, and banana plantations and all crops destroyed. There were but few lives lost.

Between 10 and 10:30 p. m., October 22, a brilliant light, which resembled a fire, was observed in the direction of Reina street.

10. *October 7-8, 1870.*—The flag indicating very bad weather has been displayed since this morning, October 7. At 1 p. m., October 7, the barometer read 29.66, and at 6:30 p. m. 29.45, and heavy gusts of wind, frequently shifting, some of great violence, continued until 9.30 p. m., at which time there was a marked decrease in the velocity of the wind, and attended by a heavy downpour of rain. The rain continued with more or less severity until 10:30 p. m., at which time the wind again increased in force to a storm of great intensity, attaining its maximum force between 12 midnight of the 7th and 3 a. m. of the 8th. At 4.30 a. m. of the 8th the barometer indicated a rising tendency, and at 12 noon read 29.67. The barometer at 3 a. m. read 29.30, indicating that the blow was a severe storm, but not a hurricane; however, it was the most severe storm since October 22, 1865.

On the morning of October 7 the wind was northeast, with a tendency to veer toward the east, which indicated that the storm center was to the southeast. The winds continued northeasterly all day, with falling barometer, indicating that the storm center was moving northwest by north. As the center approached the winds increased in force. During the afternoon the wind backed to north-northeast, indicating the storm center was to the east-southeast, having shifted its course more toward the north than during the earlier portion of the day. From sunset of the 7th to 2 a. m. of the 8th the wind backed to the north and blew with its maximum force, showing the center to be east at 2 a. m., and as at that time the barometer registered the lowest pressure, the indications were that the storm center was nearing Havana. After 2 a. m. the barometer began to rise; at 12 noon the wind backed to north-northwest and diminished in force. From the action of the barometer and winds, it would appear that the storm center moved to the northwest and to the eastward of Havana.

After 2 p. m., October 7, the ferryboat service between Havana and Regla was suspended. Considerable damage was reported to trees and banana plants in the vicinity of this city. At the Reina battery a small wooden garret was blown down. In Havana, on San Luis Gonzaja (Reina) street, and in Isabel la Catolica, Rodas, and Colon parks many trees were blown down, and some of them, including roots, were blown out of the ground. In the Plaza de Armas, in front of the Captain-General's palace, many public lanterns (street lights) were broken, as also was the lantern in front of the Tacon Theater. Some small wooden buildings were blown down. A portion of the tramway between this city (Havana) and the Vedado (a suburb)—that portion of the tracks beyond Torreon—was washed away. One of the cars was washed off the track by the waves and all the passengers drenched.

In the harbor the sloop *Zarramplin* was blown against the wharf and sunk. She was loaded with brick and petroleum the cargo was saved. Two lighters, loaded with old iron, were sunk alongside the Spanish brigantine *Patriarca San Jose*. The British frigate *Sea Gem* broke her cables and was blown against the Machina naval station wharf. A brigantine and an American schooner were riding out the storm off the Tableros, the Gulf coast to the northward of Cabaña Castle, when their anchor chains parted and they were blown on shore, but were not damaged.

In Guanabacoa, Vibora, and Arroya Apolo some damage reported to houses and trees.

In Nueva Paz 110 houses destroyed.

In Bejucal 50 houses and many trees blown down and all plantings and crops destroyed.

In Colon some houses and walls blown down; some suburbs inundated, compelling the people to abandon their houses; telegraph lines down and the roads impassible.

Reports received at Guines state that a vast amount of damage was done to Nueva Paz and San Nicolas.

In Jaruco, Bainoa, and Tibarca houses destroyed.

In Madruga more than 100 of the houses occupied by the poor people were destroyed.

In Matanzas the destruction was terrible. The districts of Ojo de Agua and Puebla Nueva have suffered great and sensible losses.

At the railway station at San Luis a landslide occurred, into which the train from Havana ran and was wrecked; very few of the passengers escaped; probably killed.

The rivers San Juan and Yumuri overflowed, their waters intermingling and inundating the country to a considerable depth. It was reported that about 40 persons were drowned and it is expected that many more cases of drowning will be reported. At the railway station at Garcia the level of the water reached the chapiters of the columns. The Pailen Bridge was destroyed. It was reported that the houses of a small sugar plantation near the San Juan River were carried away and 40 of the workmen drowned or killed; also that some employees of the Bahia railway were killed.

Another report regarding the inundation of Matanzas states that the flood carried away all the buildings of the railway station at San Luis and everything it encountered in its path; submerged a train that had remained at the station on account of the tempest, drowning 26 employees of the railway company and 30 passengers.

In the harbor of Matanzas some vessels were blown on shore and seriously damaged and the brigantine *I. N. Nicholas* totally destroyed. All crops in the territory between the meridians of Sagua and western Havana were destroyed.

11. *October 19–20, 1870.*—October 19, 2 p. m., barometer 29.67, moderately fresh east by southeast winds; 5 p. m., wind fresher, barometer 29.63; 10.30 p. m., east-southeast wind, with rain squalls, barometer 29.55; 11 p. m., barometer 29.45; 11:30 p. m., very heavy rain, southeast wind, very fresh, barometer 29.33.

October 20, 12:30 a. m.—Heavy wind, with rain squalls, barometer 29.34; 1 a. m., very heavy south-southeast wind continued with rain squalls, barometer 29.34; 1:30 a. m., strong squalls from southeast, with heavy rain, barometer 29.28; 2:30 a. m., barometer 29.25; 3 a. m., barometer 29.25; 3.30 a. m., heavy wind, with gusts, from south-southeast to southeast, barometer 29.24; at 4:30 barometer began to rise. From 4 to 4:30 a. m. wind blew very hard from the south, with gusts; 5:30 a. m., wind continued blowing from the south with less intensity, barometer 29.25; 6 a. m., barometer 29.26; 7 a. m., south-southwest wind, with squalls of heavy rain, barometer 29.27; 8 a. m. southwest wind, with rain squalls, barometer 29.30; 8:30 a. m., wind west-southwest and heavy rain, barometer 29.34; 9 a. m., barometer 29.37; 10 a. m., wind blew from south by southwest, barometer 29.42; 11 a. m., barometer 29.42; 12 noon, south-southwest wind and dark weather, heavy sea from west, barometer 29.42.

Damages are reported to houses and crops in San Cristobal and Guanajay.

At Wajay the water rose to a level of 3 feet on the streets during the night of 19–20th. Trees were broken off and blown through the air.

At Batabano the sea inundated the city, compelling the inhabitants of the lower portion to move, some using boats, to the higher portion of the city. Many houses were damaged and some destroyed, and some vessels were blown on shore.

At Cienfuegos some trees which had withstood the preceding hurricanes were blown down.

At Nueva Paz the wind veered from east-southeast to west-southwest during the evening of the 19th. During the night of 19–20th an odor like sulphur was observed.

The ravages of this hurricane covered the territory between Cardenas and Pinar del Rio, extending farther to the westward than the preceding one, and it is estimated that there will be a shortage of 50 per cent in the sugar crop, caused by these two hurricanes.

12. *September 30–October 7, 1873.*—Caimanera, at 7 p. m., September 28, the barometer read 28.66; at 10 p. m., 28.95, with a hard northwest wind and heavy sea from the southeast; after that hour the wind backed to south, with gusts of hurricane force.

October 3.—In my opinion we are under the influence of a hurricane which should form near the southernmost of the West Indies and pass to the southward of Jamaica, recurving between latitudes 20° to 21° north, near Yucatan, and it is probable that its effects will be felt on the north coast and parts of the interior of the west provinces. (Signed) *S. D. A.* [Name of writer of above unknown.—*W. B. S.*]

October 6.—A storm is approaching from the south-southeast; the barometer is falling. Should the storm be a cyclone it will probably pass to the westward of Havana toward Pinar del Rio Province, and the wind attain its greatest intensity as it veers toward the south, south-southwest, and southwest, and diminish when wind veers to the northwesterly quadrant.

During the afternoon and the night of the 6th and 7th a heavy north-northwest sea was running, reaching its greatest violence at 2 a. m. of the 7th. The interiors of nearly all of the houses at the northern end of San Lazaro street have been destroyed by the fury of the waves. The neighborhood has never experienced such heavy waves, and two or three walls that withstood the hurricanes of 1844 and 1846 have been destroyed. Some doors on the south side of San Lazaro street have been battered down. The beach at Marianao was flooded and many houses destroyed. Some trees in this city were blown down.

In the Vedado, a suburb, some houses were damaged. Morro Castle was also damaged to some extent.

Batabano was inundated.

Meteorological record at Havana, September 30–October 7, 1873.

Date.	Hour.	Barometer.	Temperature.	Wind.	Miles per hour.
			°		
September 30	4 a. m.	29.70	81.5	east-northeast.	....
October 1	4 a. m.	29.69	85.5	east.	....
October 2	4 a. m.	29.71	84.6	south-southeast.	....
October 3	4 a. m.	29.72	75.6	east by southeast.	....
October 4	4 a. m.	29.72	75.0	east.	20.1
October 4	4 a. m.	29.70	77.9	east-southeast.	20.1
October 5	4 a. m.	29.68	78.1	east-southeast.	22.4
October 5	4 a. m.	29.65	83.8	south-southeast.	26.8
October 6	4 a. m.	29.55	80.1	south-southeast.	29.1
October 6	4 a. m.	29.56	80.8	south.	33.6

13. *September 13-14, 1875.*—Lowest barometer, 29.40; at 4 a. m. of the 14th the barometer began to rise. Time of lowest barometer unknown, also place of observation, but suppose it to be Havana.—*W. B. S.*

Cardenas, September 13.—At 3 p. m. the barometer read 29.46; 4 p. m., 29.40; 5 p. m., 29.26; 6 p. m., 29.29; 7 p. m., 29.25; 8 p. m., 29.18; 9 p. m., 29.11; 10 p. m., 28.95; 11 p. m., 28.90. October 14, 2 a. m., 29.00; 6 a. m., 29.25; 8 a. m., 29.31; 9 a. m., 29.36; 10 a. m., 29.37; 11 a. m., 29.42. From 6 p. m. of the 13th to 3 a. m. of the 14th the winds were hard northeast, veering to southerly. Doors were blown in and trees blown down, but no damage was done to vessels in the harbor.

Havana, September 13, 1875.—At 5 a. m. the barometer read 29.81; 6 a. m., 29.82; 7 a. m., 29.83; 8 a. m., 29.85; 9 a. m., 29.85; 10 a. m., 29.85; 11 a. m., 29.83; 12 noon, 29.81; 1 p. m., 29.79, and continued falling until 2:20 a. m. of the 14th, at which time it read 29.29; at 2:40 a. m. it read 29.31, and continued to rise.

Portillo, Santiago Province.—At 11 p. m. of the 12th the wind blew down the majority of the houses of this town. Heavy rainfall on the night of the 11-12th, being heaviest on the morning of the 12th, caused the river to overflow, washing away the few houses that had withstood the violence of the wind. At 4 a. m. on the 13th the barometer read 29.00.

Rev. Father Viñes says that this cyclone (?) was of mild intensity. He states that its center entered the island somewhat to the east of Cape Cruz, passing near Manzanillo and Santa Cruz, then passed to the southward of Puerto Principe, Santa Clara, Colon, Cardenas, and Matanzas, and to the north-northeast and north of Havana. The districts in which the greatest damage was done were Portillo, Mazanillo, and Santa Cruz.

14. *October 12-13, 1876.*—A cyclone passed St. Thomas and Porto Rico and continued moving west-northwest, passing through and off the north coast of the Island of Cuba.

During the forenoon of October 19 the vortex passed Havana; the lowest barometer was 28.68, between 11:30 and 11:40 a. m. The area of calm reached Havana 11:40 a. m. and continued for some time, after which the wind blew from the northwest, west-northwest, and west, and at 1:13 p. m. became steady from the west-southwest, which was the opposite direction (east-northeast) from which it was blowing during the first part of the hurricane. After the wind backed to northwest the barometer began to rise rapidly. Hard gusts of wind and very frequent rain squalls have occurred since the storm's effects began to be felt, and the clouds, which were from the same direction as the wind, were very low and near to the house tops, and shifted their direction with the wind as it backed to northwest, west-northwest, and west-southwest, and continued moving from the latter direction until 10 p. m.

The damage done by this hurricane was as follows: Some damage to vessels in the harbor and also to the wharf at the office of the captain of the port. In the city some buildings and many trees were blown down. In the country the devastation was much greater, and houses and crops were destroyed.

In the harbor of Mariel 1 Spanish gunboat, 7 merchant schooners, and 1 sloop were blown on shore. In the City of Mariel the wind greatly damaged many houses, principally the roofs, and blew down many trees.

Damage to buildings was reported from Mantanzas, where many trees were blown down; in the harbor 2 schooners and 1 launch were greatly damaged, a bark lost one mast, and 7 fishing boats were totally destroyed.

In Cienfuegos some houses were blown down, and the river overflowed, the inundation extending as far as Corales street, between Santa Cruz and Santa Elena streets, and some vessels at anchor in the harbor were damaged.

In Gura de Macuriges the river overflowed, inundating the village. The current of the water in the inundated district was so swift that persons could not cross the streets. Houses were severely damaged, but no person suffered injury.

At Artemisa it is reported that never before has a hurricane occurred attended with such violent winds at this place. All that portion of the island (Cuba) between the meridians of Santa Clara and Pinar del Rio have suffered greatly; much damage was done to the canes; small crops were destroyed; trees were blown down; rivers overflowed; and many buildings, both in the city and country, were more or less damaged and some totally destroyed. No loss of life has been reported.

15. *September 5-6, 1882.*—The center of the cyclone (hurricane) passed Havana shortly after midnight of the 5th, moving toward the west-northwest, with moderate velocity of progression. The diameter of the storm center was small and its force of moderate intensity, less than that attained at Cienfuegos. The lowest pressure, 29.60, occurred at 1:30 a. m. The hardest gusts of wind occurred between 1 a. m. and 2 a. m., attaining a force of 38 to 40 meters per second (85 to 89.5 miles per hour), while the average velocity during that time was 19.5 meters per second (43.6 miles per hour). The heaviest winds at Havana were from the northeast and east. After passing Havana the rate of progression was greatly increased; the direction was continued toward the west-northwest, indicating that the center was still a considerable distance from the latitude of recurve, which possibly would not occur until it had approached near to the Texas coast; then cross the United States toward Cape Hatteras (to the southward of Cape Hatteras). At 1 p. m. telegraphic communication was possible with Matanzas, Bejucal, and Guanajay, but impossible with other points. Very little damage was reported to vessels in the harbor; the floating dock broke away from its anchors and was blown into the center of the channel, where it was sunk, by order of the dock superintendent. On account of being insecurely anchored, 1 American brigantine and 2 Spanish schooners incurred some small damages.

At Batabano the wind blew very hard from the north, veered to north-northeast, and during the night to the east. Some fishing schooners were blown on the beach.

Cienfuegos, September 5.—At 1:30 p. m. south-southwest winds blew with hurricane velocity; weather totally cloudy and dark; barometer 29.36; hurricane moving west-northwest, in which direction the center lies. The maximum velocity of the hurricane was experienced at 10:30 a. m., when the barometer read 29.13, and the winds were westerly. Much damage was done to buildings; no loss of life reported.

In Santa Clara many houses were blown down. The vortex of the hurricane passed that city between 8 and 8:45 a. m., September 5, preceding which, very violent northwest winds, with gusts of hurricane velocity, blew. At 8 a. m. the wind died to a calm and so continued until 8:45 a. m., when it shifted to the east, and blew with increasing velocity, attended with frequent rain squalls. At 2 p. m. the wind still continued blowing very hard, with a tendency to veer to the south. Almost all the houses in the country and crops were destroyed.

In Sagua la Grande some damage was done to houses, and in the harbor four lighters loaded with sugar were sunk, and an English schooner was blown on the beach.

At Cardenas some minor shipping was blown against the wharf and damaged.

Reports have been received from other towns between the meridians of Santa Clara and Havana, stating that the hurricane caused considerable damage to houses, some of which were blown down, and crops were very much damaged.

16. *October 8, 1882.*—Batabano, 7:30 p. m., barometer 29.90; state of weather, raining; winds fresh and variable between east-southeast and east.

Cienfuegos, October 7.—Bad weather; heavy sea from the south. October 8, 10 p. m.: Since 4 p. m. yesterday the barometer has been falling, now reads 29.78; temperature 77°; weather cloudy; light northeast wind.

Bejucal, October 8, 8:15 a. m.—Heavy weather continues, with strong gusts of wind and heavy showers; barometer falling very slowly and slightly; now thundering and lightning,

Santiago de Cuba, October 8, 3:05 a. m.—Guantanamo reports barometer reading low. Here the weather is threatening, with rain squalls; wind southeast.

"This storm was of very great diameter, and its influence was felt over extensive areas on the 8th, from Guantanamo to Vera Cruz. Its center passed the western portion of the island and recurved over the Tropic of Cancer, and is at present, 2 p. m., October 9, toward the west-northwest. The majority of the gusts of wind experienced in this city were from 22 to 25 meters per second (49 to 56 miles per hour) in force, while the average velocity of the wind during the blow was 14 meters per second (31 miles per hour). (Signed) *Benito Viñes, S. J.*"

17. *August 21-26, 1886.*—Trinidad, Cuba, August 26, 1886, reports received here by mail state that great damage was done by a hurricane in Jucaro, and many coastwise vessels were severely damaged, while several others are still missing. No lives lost so far as known. (Signed by the captain of the port of Casilda.)

Ciego de Avila.—At 2 p. m. of August 22 the wind began to blow very hard, with gusts of hurricane force, blowing the tiles from the house roofs, and attended with heavy rain. At 4 a. m. the wind and rainfall were terrific; houses were blown down, crushing many of their inhabitants; the streets were flooded, in places to a depth of 80 centimenters (2.6 feet). The maximum intensity of the hurricane was experienced during the two hours from 7 to 9 a. m., during which time roof tiles and zinc plates were carried through the air with extraordinary velocity. The majority of the large trees were uprooted, and houses were blown down with a terrible crash. At 9 p. m. the wind began to decrease, but the rain continued falling in excessive amounts. About 150 houses were blown down, rendering more than 200 families homeless; and the remaining buildings of the town, more than 400, were more or less damaged. In Jucaro only two buildings in the town withstood the violence of the hurricane. All the banana plants and other crops in this territory were destroyed. Of the corn crop, which was ready to be harvested, not one cob remains, having been blown to, no one knows where; forest trees were uprooted and roads destroyed.

Jucaro, August 21, 9 a. m.—Barometer, 29.61; thermometer, 71.6°; hard northeast wind; weather, cloudy; 9 p. m., barometer, 29.68; thermometer, 71.6°; hard northeast wind; state of weather, raining. 22d, 5 p. m., barometer, 29.61; thermometer, 68°; north winds with hurricane velocity; 9 p. m., barometer, 29.72; thermometer, 66°; winds veering to northwest, to southwest; storm over.

Caibarien.—On the 22d, at 1 a. m., the winds began to increase in force, with some hard gusts, from the east-northeast, attended with rain squalls; barometer falling. The waves began to inundate the wharf. Very hard east-northeast and northeast winds blew until 2 p. m., at which time they backed to north and began to diminish in force. The weather did not present the aspect of a hurricane, rather that of a severe cyclonic storm; the clouds were high and divided.

18. *Manzanillo, September 20-22, 1886.*—The lowlands throughout this district and a part of Bayamo were inundated by the storm of September 20, 21, and 22. All crops were destroyed; more than 350 cattle and a great number of sheep and pigs and some horses were drowned. In some of the country districts the people had to seek shelter on the house tops, from which they were rescued by means of boats.

19. *Isabella, harbor of Sagua, September 3, 1888.*—At 9 p. m. barometer was 5.5 mms. (.216 inch) below the normal; winds northeast, 15 meters per second (33.6 miles per hour); weather cloudy; eastern horizon dark; rain squalls occurred between 6 and 8 p. m.; wind increased in intensity after 8 p. m. (Signed) *Captain of the Port.*

Caibarien, September 3, 1888, 9:15 p. m.—Barometer 4 mms. (.158 inch) below normal and falling; weather bad, with rain squalls from the north. (Signed) *Captain of the Port.*

Jucaro, September 3, 6 p. m.—Barometer 5 mms. (.197 inch) below the normal; thermometer 18° C. (64.4°); north-northeast winds, 14 to 20 miles per hour; weather bad. (Signed) *Captain of the Port.*

In Havana, since the morning of September 4, the winds have backed slowly from north-northeast to north to north-northwest. During the afternoon the winds were steady from the north and north-northeast, with very little shifting of direction; gusts of wind, increasing in force each moment, attended by rain squalls and rapidly falling barometer, which indicate that the hurricane is moving toward Havana. After sunset the wind veered to north-northeast, and after midnight September 4, at which hour the pressure recorded its lowest readings, it rapidly veered to east and east-southeast, and the gusts diminished in intensity.

From the telegrams received it appears that the center of the hurricane passed to the northward of Gibara and entered the island to the eastward of Sagua; moved across the island, passing to the southward and near to Havana. The minimum barometer reading, 731.91 (28.82 inches), occurred between 12 midnight, 4th, and 12:30 a. m., 5th; the maximum force of the gusts of wind was 42 mms. per second (94 miles per hour), and the total rainfall 8.63 mms. (3.40 inches).

At 4 p. m., 4th, a boat, under sail, from the man-of-war *Jorge Juan* was overturned and two sailors drowned. The tug *Valador* was sunk at the gas company's wharf; many vessels in the harbor suffered more or less injury; railway and ferryboat traffic was stopped; many buildings were seriously damaged, some of them having their roofs blown off, and many trees blown down.

Marianao reports considerable damage to houses.

Batabano, September 4, 1888.—From daybreak until 12 noon fresh, gusty north-northwest winds blew and in consequence the level of the water in the harbor was lowered. At 9 p. m. threatening weather continued, with indications of a hurricane; barometer 29.70, thermometer 80.6°; constant heavy rains, with occasional rain squalls; weather dark and lowering. At 12:30 p. m. the wind backed to southeast and south-southeast and drove in the water from the sea, inundating the town. At 6 a. m. of the 5th all of the houses were flooded, the water reaching to the height of a man's waist in the houses and still higher in the streets. The Spanish gunboat *Lealtad* was capsized when, at 11:30 p. m. of the 4th, the wind backed to northwest and west and increased to hurricane intensity, and the captain, a second lieutenant, and 8 men were drowned.

Guanajay reports that some of the houses in the country were blown down and all crops destroyed and that the hurricane was something terrific.

Matanzas reports that the maximum force of the hurricane was felt at 9 p. m. of the 4th. Some damage reported to the roofs of houses and to lanterns of the city lighting service; very heavy seas damaged the houses along the beach; some vessels were blown on shore and seriously damaged. The captain and two passengers of the sloop *Antonio Saurez* were drowned and the sloop *Almirante*, with her entire crew, has disappeared.

In Sabanilla some houses damaged and one person killed.

At Sagua the river overflowed and many persons were killed by the hurricane. The suburb of Pueblo Nuevo, located at the mouth of the river, was totally destroyed. At Isabella, harbor of Sagua, numerous houses were carried away and the harbor was filled with floating doors, furniture, etc. The office of the captain of the port was entirely surrounded by the sea and the iron tanks for holding fresh water were carried into the house by the violence of the hurricane. A railway train was overthrown upon its arrival at the station and the passengers more or less injured; the rails were carried away. When the steamer *Adela* sailed from Isabella at 2 p. m. on the 5th, 45 bodies had been recovered, and it is thought that double that number perished by the inundation. From Sagua to Cape San Antonio the loss to houses, crops, and trees in the country has been considerable. Sixteen persons perished by the capsizing of a boat, in which they had endeavored to cross from Salto, near Sagua, to a nearby beach.

In Cienfuegos from midnight of the 3d until midnight of the 4th the barometer fell, reaching its minimum, 29.32, at the latter time. At midnight of the 3d the wind began to increase in force from the northwest. At noon of the 4th it backed to west and in the afternoon to southwest, from which direction the maximum intensity was experienced. From 10 p. m. of the 4th to 2 a. m. of the 5th the wind blew from the south, then backed to southeast and diminished in force. In the early morning of the 4th a drowned fisherman's body was found on Santa Elena street. Great damage was done in the country and all crops were destroyed.

Two hundred head of cattle were drowned in the Santo Domingo district.

In the Paula municipality 92 families were rendered homeless.

Batabano reports many fishing schooners capsized and others blown on shore.

In Caibarien a falling wall killed an old man and injured other persons, and on the cayos two families of fishermen, each lost three sons.

In Vueltas the loss is estimated at $400,000.

In Sancti Spiritus banana plantations and corn and rice crops were destroyed.

All tobacco seed plots in the Vuelta Abajo were destroyed. In Pinar del Rio 75 houses were damaged.

20. *Havana, September 24, 1894.*—At 1 p. m. the barometer began to fall slowly, attended with rain squalls from the north and northeast, and the weather becoming darker and darker. At 4 a. m. of the 25th the barometer began to fall more rapidly, with very hard gusts of wind from the north-northeast. At 8 a. m. the barometer continued falling, with violent north and northeast winds, steady rainfall, and dark weather. At 10 a. m. the wind began to diminish somewhat, but the barometer continued to fall until 4 p. m., reading at that hour 29.35, attended with light rain and moderate gusts of west-northwest wind. At 6 p. m. the barometer showed indications of rising, and at 8 p. m. it began to rise.

At Matanzas the banana plants were blown down, and some damage was done to houses in the country.

In Cardenas some wooden partitions in the courts of houses were blown down.

In Marianao the public baths were destroyed, and some small houses occupied by fishermen were somewhat damaged.

In Cienfuegos great damage was done in the suburbs by the storm; 3 persons killed and crops greatly damaged.

In Santa Clara no serious damage was done by the storm to buildings, but some cattle were killed and crops greatly damaged.

At Sancti Spiritus the river Zaza overflowed, carrying away the wharf and doing some damage to buildings.

In Sagua ugly weather began on the 23d and continued through the 24th; gusts of wind and rain squalls did considerable damage to cane and banana plantations. The Sagua and Yabucito rivers overflowed; the plantation Salvador was inundated and the canes blown flat by the wind totally destroying the crops, so that the central will not be able to grind this year. It is believed that 6 or 7 of the plantations in this vicinity have been flooded, and that the cane crop will, therefore, be about 50 per cent short. At 4 a. m. of the 25th the waters reached the city and inundated it. The waters continued to rise until noon, after which hour they fell. The overflowing of the rivers created three currents in the city, along Muras, Oriente, and Progreso streets, through which the entire city was inundated, except Tacon street, between Sol and Aurora. The flood reached a maximum height of 7 to 9 meters (23 to 29.5 feet) along the river bank; 1.5 meter (4.9 feet) at the railway station; 2 meters (6.6 feet) at the post office, and 2.5 meters (8.2 feet) at the Telegraph Hotel. The Spanish Club was flooded to a depth of 3 meters (9.8 feet), and all the furniture therein was carried away by the waters; the house of the French consul and that of Notary Montero were totally destroyed. The flood reached to a distance of 7 kilometers (4.3 miles) to the eastward; 5 kilometers (3.1 miles) to the eastward, and an unknown distance to the southward. There were 8 persons drowned, also a family living on the Santa Teresa plantation. The schooner *Vistona* was wrecked at the caballeria of the civil guards. The loss is estimated at $500,000. Over 7,000 persons saved themselves by climbing to the roofs of the houses, and 400 to the tops of the churches.

In Trinidad the cross on the church of Santisima Trinidad was blown away by the wind, and some houses considerably damaged. All crops were totally destroyed. The river Agabama overflowed, causing a very serious inundation.

In Santa Cruz del Sur 46 houses were destroyed, and considerable other damage done.

W. B. Stockman,
Forecast Official Weather Bureau.

THE HURRICANES OF 1780.

Colonel Reid, in the Law of Storms, gives exhaustive descriptions of the great hurricanes of 1780:

Three great storms occurred in that year nearly at the same time, and these have been frequently confounded together and considered as but one. The first destroyed the town of Savannah la Mar, Jamaica, on the 3d of October; the second, and by far the greater one, passed over Barbadoes on the 10th and 11th of October, and the third dispersed and disabled the Spanish fleet, under Solano, in the Gulf of Mexico after it had sailed from Havana to attack Pensacola. The Savannah la Mar storm has been described in this paper.

THE GREAT HURRICANE OF 1780.

This storm, coming from the southeast, passed over Barbados on the 10th and 11th of October, and the ships of Admiral Hotham's squadron experienced the hurricane, each in turn, according to the place she was in, and it passed on until it reached the ships of Sir Peter Parker at Jamaica.

The *Deal Castle* was wrecked at Porto Rico. The *Ulysses* and *Pomona*, with the fleet under their convoy, were in the Mona Passage and suffered greatly, being almost in the center of the storm. The *Diamond* and *Pelican* had been sent to Honduras, convoying merchant ships, and had felt nothing of the first hurricane, but on their return toward Jamaica, though on somewhat different courses, both ships came within the influence of the great hurricane of the 15th of October. The *Thunderer*, on her way to Jamaica from St. Lucia, foundered in one of these storms, but where and on what day has never been ascertained.

The *Berwick* had separated from this fleet after the hurricane of Savannah la Mar and was proceeding to England under jury masts. She had reached north of the latitude of Bermuda when the second hurricane overtook her, and, by her track and log book, we are enabled to ascertain the direction taken by this storm. On reading the logs of these ships and the various accounts of this hurricane, and comparing the different reports of the wind, it will be found that no storm yet described more strongly proves than this the rotary nature of hurricanes, and, after attentive consideration of this tempest, in addition to the details of so many others, it seems difficult to refuse belief to this being their mode of action. The center of the circle would appear to have passed just to the north of Barbados and thence over the Island of St. Lucia, so that Admiral Hotham's ship, the *Vengeance*, which remained in the careenage, to ride out the gale, was in the right-hand semicircle of the storm, whilst the ships which cut or parted their cables, and ran first to the southward, were for a while in the left-hand semicircle. These last appear to have been dismasted and the *Vengeance* drove on shore just as the center of the storm was passing between them. The three ships to the eastward of Martinique, being in the right-hand semicircle, had the gale from the eastward and were therefore upon a lee shore. By the log of the *Endymion*, it will be seen that ship just cleared the northeast point of the island, but the *Andromeda* and *Laurel* were wrecked and 25 men of the crew alone were saved. These men, of course, were made prisoners, but were sent by the Marquis de Bouille to the British Governor of St. Lucia with a letter expressing that he could not detain them as prisoners from the chances of a catastrophe common to all.

A Danish report was made by Captain Stockfleth, who commanded the frigate *Christiana*, to the Danish Admiralty. This ship met the hurricane on the 13th of October, 1780, when southwest of Porto Rico, but the direction of the wind is not given. The report states that only six or seven ships of the French convoy at Martinique were saved, and from Sir Peter Parker's report we learn that there were 5,000 troops on board. From St. Lucia the center of the storm appears to have passed over or very near to the Island of Mona on the morning of the 15th of October, and when we take up the logs of the *Venus* and *Convert*, which were on one side of the storm at that date, and those of the *Diamond* and *Pelican*, which were on the other side of it, we find the wind blowing in contrary directions. On referring to the logs of ships lying in the harbor of Antigua we there find the wind blowing in squalls, at first coming from the east-northeast, then veering by the east to the southeast, in strict accordance with the apparent law of storms in the Northern Hemisphere.

The squadron of Admiral Rowley, being in latitude 26° 30′ (about which latitude we find hurricanes so frequently change their direction and set toward the eastward), first received the storm easterly. As the gale proceeded toward the northeast this squadron was in its left-hand semicircle.

By referring to the log books of His Majesty's ships *Strewsbury* and *Resolution*, it appeared that they were under weigh off Long Island on the 18th of October, 1780. The weather had been fine for some time, both before and after, and the only exception was that day, when it blew in squalls so as to make these ships strike their top-gallant masts, and the *Shrewsbury* split a topsail, the wind becoming north. At Bermuda 50 vessels were driven on shore on the 18th of October, and we have here the log of the *Berwick* for that day, when she was to the northward of that island, from which we get the direction of the wind. The wind, as laid down from the *Berwick's* log book, accords with the reports of living witnesses (1839) at Bermuda, and this storm is there still referred to as the greatest ever experienced in their latitude. Thus, the great hurricane is traced beyond Bermuda, moving in the direction of the Azores; and if this same storm was really the cause of the *Shrewsbury* and the *Resolution* striking their top-gallant masts, and they increase in diameter as they proceed toward the poles, this storm, on reaching the latitude of Great Britain, may have given a circular direction to the wind over an extent equal to the width of the Atlantic from the British Islands to Newfoundland.

Copy of an account of the hurricane of the 10th of October, 1780, which was sent to Lieutenant-General Vaughan, Commander-in-Chief of the Leeward Islands, and by him transmitted to Lord G. Germaine. Copied from the Gentleman's Magazine of 1780:

The evening preceding the hurricane, the 9th of October, was remarkably calm, but the sky surprisingly red and fiery. During the night much rain fell. On the morning of the 10th much rain and wind from the northwest. By 10 a. m. it increased very much. By 1 p. m. the ships in the bay drove. By 4 p. m. the frigate *Albemarle* parted and went to sea, as did all the other vessels, about 25 in number. By 6 p. m. the wind had torn up and blown down many trees, and foreboded a most violent tempest. At government house every precaution was taken to guard against what might happen; the doors and windows were barricaded, but it availed little. By 10 p. m. the wind forced itself a passage through the house from the north-northwest, and the tempest increasing every minute, the family took to the center of the building, imagining, from the prodigious strength of the walls, they being three feet thick, and from its circular form, it would have withstood the wind's utmost rage; however, by half past 11 they were obliged to retreat to the cellar, the wind having forced its passage into every part and tore off most of the roof. From this asylum they were soon driven out; the water, being stopped in its passage, having found itself a course to the cellar, they knew not where to go. The water rose four feet, and the ruins were falling from all quarters. To continue in the cellar was impossible; to return to the house equally so. The only chance left was making for the fields, which at that time appeared equally dangerous. It was, however, attempted, and the family got to the ruins of the foundation of the flagstaff, which soon after giving way, every one endeavored to find a retreat for himself. The governor and the few that remained were thrown down, and it was with great difficulty they gained the cannon, under the carriage of which they took shelter. Their situation here was deplorable. Many of the cannon were moved, and they had reason to fear that the one under which they sat might be dismounted and crush them by its fall, or that some of the ruins which were flying about might put an end to their existence; and, to render the scene still more doubtful, they were near the powder magazine. The armory was leveled to the ground, and the arms scattered about. Anxiously did they look for break of day, flattering themselves that with the light they would see a cessation of the storm; yet when it appeared little was the tempest abated. Nothing can be compared with the terrible devastation that presented itself on all sides; not a building standing. The trees, if not torn up by the roots, were deprived of their leaves and branches, and the most luxuriant spring changed in this one night to the dreariest winter. It is yet impossible to make a calculation of the number of souls that have perished; whites and blacks together, it is supposed to exceed some thousands. Many were buried in the ruins of the buildings, many fell victims to the weather, and a great number were driven into the sea and there perished. The troops suffered inconsiderably, though their barracks and hospitals were early blown down. What few public buildings there were are fallen in the wreck; the fortifications have suffered considerably. The buildings were all demolished, for so violent was the storm here, when assisted by the sea, that a 12-pounder gun was carried from the south to the north battery, a distance of 140 yards—on its carriage, of course, which had wheels. The loss to this country is immense; many years will be required to retrieve it. Alarming consequences were dreaded from the number of dead bodies which lay uninterred, and from the quantity of fish which the sea threw up; but these alarms soon subsided.

At St. Christopher many vessels were forced on shore. At St. Lucia all the barracks and huts for His Majesty's troops, and other buildings in the island were blown down and the ships driven to sea, and the *Amazon*, Captain Finch, miraculously escaped foundering. At Dominica they suffered greatly. At St. Vincent every building was blown down and the town destroyed. At Grenada 19 sail of loaded Dutch ships were stranded and beat to pieces. At Martinique all the ships were blown off the island that were bringing troops and provisions. On the 12th, 4 ships foundered in Fort Royal Bay and the crews perished. The other ships were blown out of the roads. In the town of St. Pierre every house is blown down, and more than 1,000 people have perished. At Fort Royal the cathedral, 7 churches, and other religious edifices, many other public buildings, and 1,400 houses were blown down. The hospital of Notre Dame, in which were 1,600 sick and wounded, was blown down, and the greatest part of these persons buried in the ruins. The number of persons who perished in Martinique is said to have been 9,000. At St. Eustatius the loss was very great. On the 10th of October, at 11 in the morning, the sky on a sudden blackened all around; it looked as dismal as night, attended with the most violent rain, thunder, lightning, and wind ever known before. In the afternoon the gale increased. Seven ships were driven on shore near North Point and dashed to pieces on the rocks, and their crews perished. Nineteen vessels cut their cables and went to sea, and only one is yet returned. In the night every house to the northward and southward was blown down or washed away, with the inhabitants, into the sea, a few only escaping. The houses to the east and west were not so much hurt till the afternoon of the 11th, when the wind on a sudden shifted to the eastward, and at night it blew with redoubled fury and swept away every house. The old and new forts, the barracks, and hospital, the cathedral, and 4 churches stood. Between 4,000 and 5,000 persons are supposed to have lost their lives in St. Eustatius.

Extract from Sir George Rodney's official report of the hurricane of the 10th of October, 1780, at Barbados:

No naval stores of any kind can be got at Barbados or St. Lucia, owing to the dire effects of the hurricane which happened on the 10th of October. It is impossible to describe the dreadful scene it has occasioned at Barbados, and the condition of the miserable inhabitants. Nothing but ocular demonstration could have convinced me that it was possible for the wind to cause so total a destruction of an island remarkable for its numerous and well-built habitations, and I am convinced that the violence of the wind must have prevented the inhabitants from feeling the earthquake, which certainly attended the storm. Nothing but an earthquake could have occasioned the foundations of the strongest buildings to be rent; and so total has been the devastation that there is not one church, nor one house, so I am well informed, but what has been destroyed. I leave their lordships to judge how much my concern must have been heightened upon the report made to me of the loss His Majesty and the public had sustained in the destruction of ships of war, and the gallant officers and men belonging to them, a list of which I have the honor to inclose. But I hope some of them have escaped and arrived at Jamaica, to which island I shall dispatch an express, acquainting Sir Peter Parker with the great disaster which has happened, and request and demand his assistance, in not only hastening such of my squadron as may have escaped the hurricane and arrived at Jamaica to rejoin me, without loss of time, with the *Thunderer* and the *Berwick*, in pursuance to the orders he received by Commodore Walsingham.

SOLANO'S STORM, 1780, AND THE WINDS CALLED "LOS NORTES."

This third storm, like that which destroyed Savannah-la-Mar, has generally been confounded with the great Barbados hurricane which disabled Rodney's fleet, although it appears to have been a distinct one. It will serve to show that the gales of the Gulf of Mexico are sometimes at least of the same rotary nature as those which have been described. It is possible that the Spaniards may apply the term nortes, or norths, to more than one phenomenon, but the violent north winds in the neighborhood of Vera Cruz are frequently no other than the left-hand side of rotary storms in their northerly progression across the Gulf of Mexico, just as Redfield's storms, in their northerly progression, have been clearly shown to be in reality identical with Franklin's northeast storms.

I am indebted to Lord Clarendon, formerly British Ambassador at Madrid, for copies of documents relative to Solano's storm, extracts from which are here printed. These records show that the Spanish Admiral's flagship was in the northern half of a circular storm, for the wind commenced at northeast, veered to southeast, and ended at south-southeast. It is possible that this storm may have had its origin near the west end of Cuba, for the weather at this period was moderate and fine at Jamaica; and we find no trace of it in any of the log books of Sir Peter Parker's squadron. The British frigate *Phœnix*, just before she was wrecked, had come from Pensacola, and she had looked into Havana Harbor and seen Solano's fleet lying there. On the morning of the 15th the wind at Havana was southeast; on that day Solano, having first consulted the pilots, called together the captains of the fleet, when it was determined to sail the next day, provided the wind did not veer from the southeast quarter to south. Next morning, the 16th of October, the wind being light and more easterly, the signal was made to weigh, and 58 ships out of 74 got out of the harbor before night, and they were all out at 9 p. m.

Extract from the journal of the Spanish Admiral, Don Jose Solano, having his flag on board of the *San Juan*, commanded by Pereda:

"October 16, 1780.—At daybreak, after a moderate land breeze from east and east-southeast, the scud moving in the same direction, it fell calm. The wind afterwards sprung up again from the east-southeast quarter and freshened, and at 6 a. m. the signal was made to heave short. The wind appearing settled in the east, the signal was made to weigh anchor, and the *Caiman* ordered to wait to see all the vessels out of port. By half past 9 the Admiral was a league from the land, standing on under topsails only, in order to unite his fleet. In this manner he stood on a northerly course with the same sail during the rest of the day, with the wind varying from east to northeast. By sunset the *Velasco*, *San Genaro*, and *San Ramon*, with 7 transports, had not got out of port. The Admiral kept the same sail upon his ship during the night. October 17: At dawn it was calm in shore; by 8 o'clock a breeze sprung up from the northeast; 58 ships and vessels were in sight out of 74, the *Velasco* and *San Genaro* being among the missing ships. At 7 o'clock the *Caiman* made a signal that all the vessels had got out of port by 9 o'clock the night previous. The Admiral, concluding that the missing ships were either covered by the haze or that they had got ahead of him during the night, made sail in the course north 10° west. By noon the wind freshened at northeast, scud and heavy clouds closing in upon us, the *San Juan* carrying her foresail and topsails, lowering and raising the latter occasionally in order to keep the fleet together. At 9 p. m. the breeze freshened; took in the topsails; toward evening we could only just see the vanguard owing to the density of the clouds. At 6 p. m. reefed the foresail. By 10 at night the wind increased and was then at northeast-quarter-east, with torrents of rain and some hard squalls, shifting as far as east-northeast. October 18: At daybreak heavy clouds, rain, wind, and sea; 2 ships and a brig of the convoy in sight. At 9 a. m. the wind was east-northeast. At 10 a. m. a ship near us, which we took to be the *Guerrero*, made a signal that she was leaky. A squall coming on we could make out no more, and we then lost sight of all ships; furled the close-reefed foresail and lay to under a mainsail, the ship laboring very much. From the 18th to the 20th, continued lying to in the fourth quadrant; the weather still dark and increasing; the wind at northeast; continued rain, with a heavy sea; kept two pumps constantly working. At 10 p. m. on the 20th our tiller broke; secured the rudder; the ship sustained heavy and repeated squalls, whilst she came up from the east-northeast as far as east, as the wind veered round from the southeast to the south-southeast. October 21: By half past 4 in the morning the wind changed, making the ship come up head to sea. The ship then pitched away all her masts as well as her bowsprit, and with it lost the greater part of the cutwater. By the exertion of the officers and crew the wreck was cleared up by 6 o'clock; at this hour it began to clear up from the south-southeast. Lightened the decks of everything we could. The sea ran so high that we were still unable to ship another tiller. At 11 a. m. set topgallant-sails on the stumps of the main and fore masts and the sail of the launch on the stump of the mizzen, keeping her head to the northeast. At noon, latitude 26° 42′ north, longitude 86° 11′ west of Greenwich. October 22: Commenced with less sea and wind. At daylight saw a large vessel; we fired three guns, but she did not answer our signals. Got another tiller shipped; prepared jury masts and sails, but the ship would not wear and we could not set them. At noon fell in with the brig ***Industria***, which had received no damage, and we were the only vessel, excepting one (name unknown), that she had fallen in with since the 17th; she had laid to all the time. The ***Industria*** was ordered to keep along with the Admiral. In the evening spoke the transport ***St. John the Baptist;*** she had not suffered much. October 23: At daybreak found ourselves close to the frigate ***Rosalia***, the captain of which came on board. During the first four days of the storm the ***Rosalia*** lay to, but on the fifth she scudded with her spritsail for a foresail. Toward the end of the storm, for eight hours, she was in a complete hurricane; her seams had opened and she leaked both through the decks and sides. By the assistance of her boats we were enabled to wear the *San Juan*, after which we got up the jury-rigging. The Admiral calling a council, it was determined upon returning to Havana; orders were therefore given to Captain Pereda (captain of the *San Juan*) to proceed to that port and to conduct thither all the ships he should fall in with. The Admiral shifted his flag on board the ***Rosalia***, leaving the *San Juan* rigging jury-masts in latitude 27° 20′ north, longitude 89° 21′ west of Greenwich. The Spanish Admiral then sailed for Pensacola; after cruising in that neighborhood for some time, without finding any of his ships, he left it, and on the 16th of November he reached the Tortuga soundings, which had been ordered as a point of rendezvous; finding no vessels there, he sailed for Havana and arrived there on the 19th, and there found his fleet."

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Chart I. Tracks of West Indian Hurricanes. May, 1878-1900.

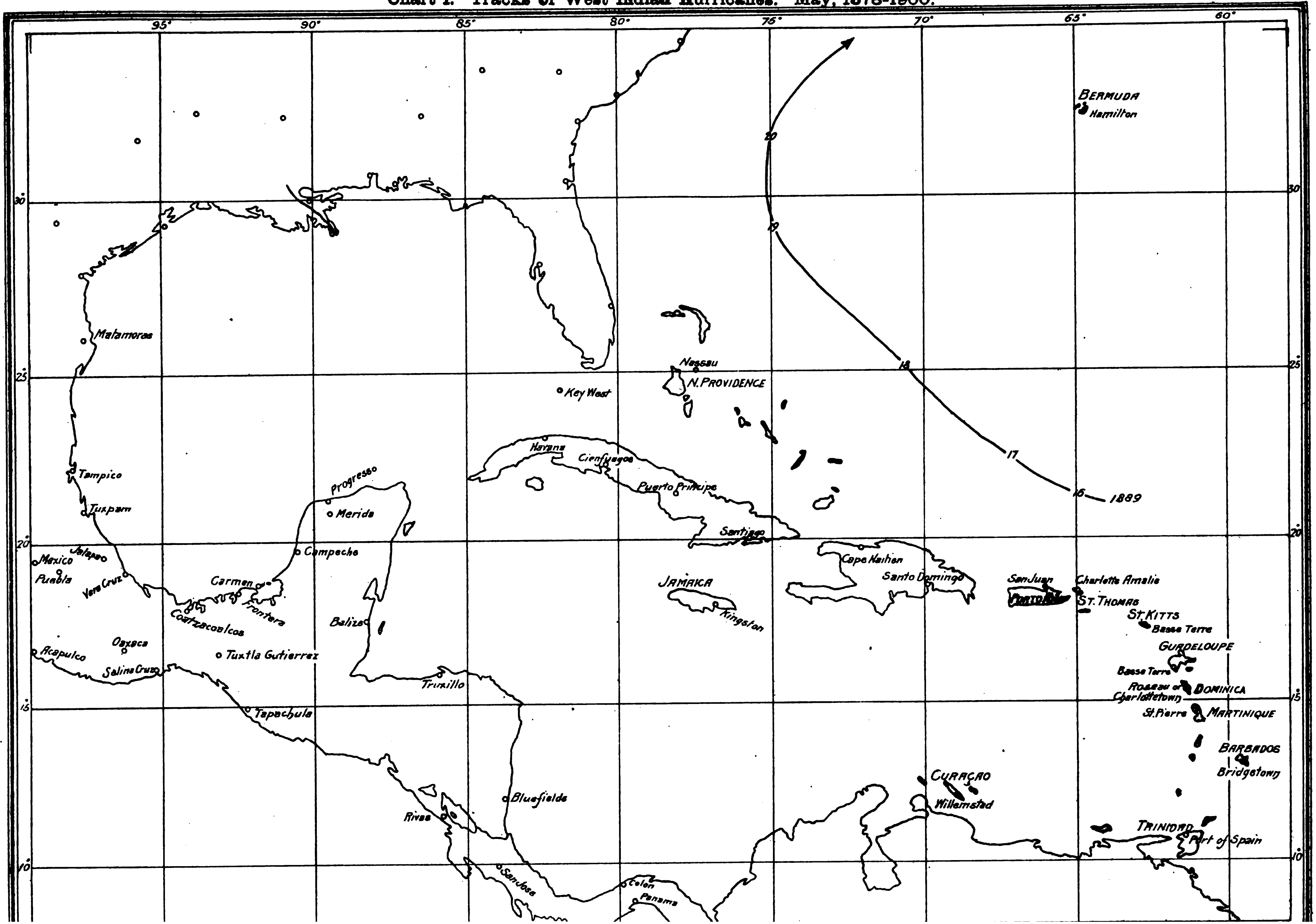


Chart II. Tracks of West Indian Hurricanes. June, 1878-1900.

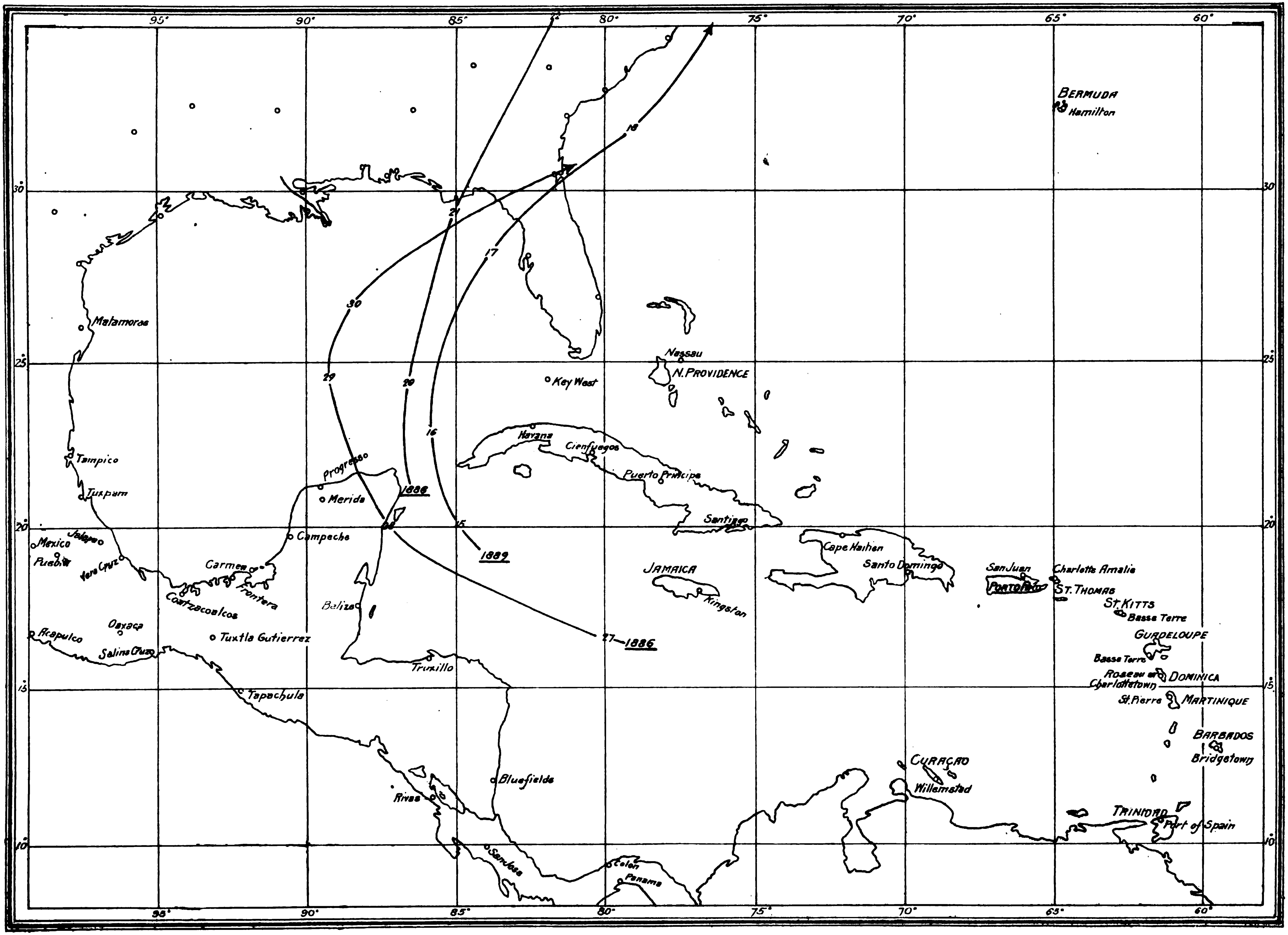


Chart III. Tracks of West Indian Hurricanes. July, 1878-1900.

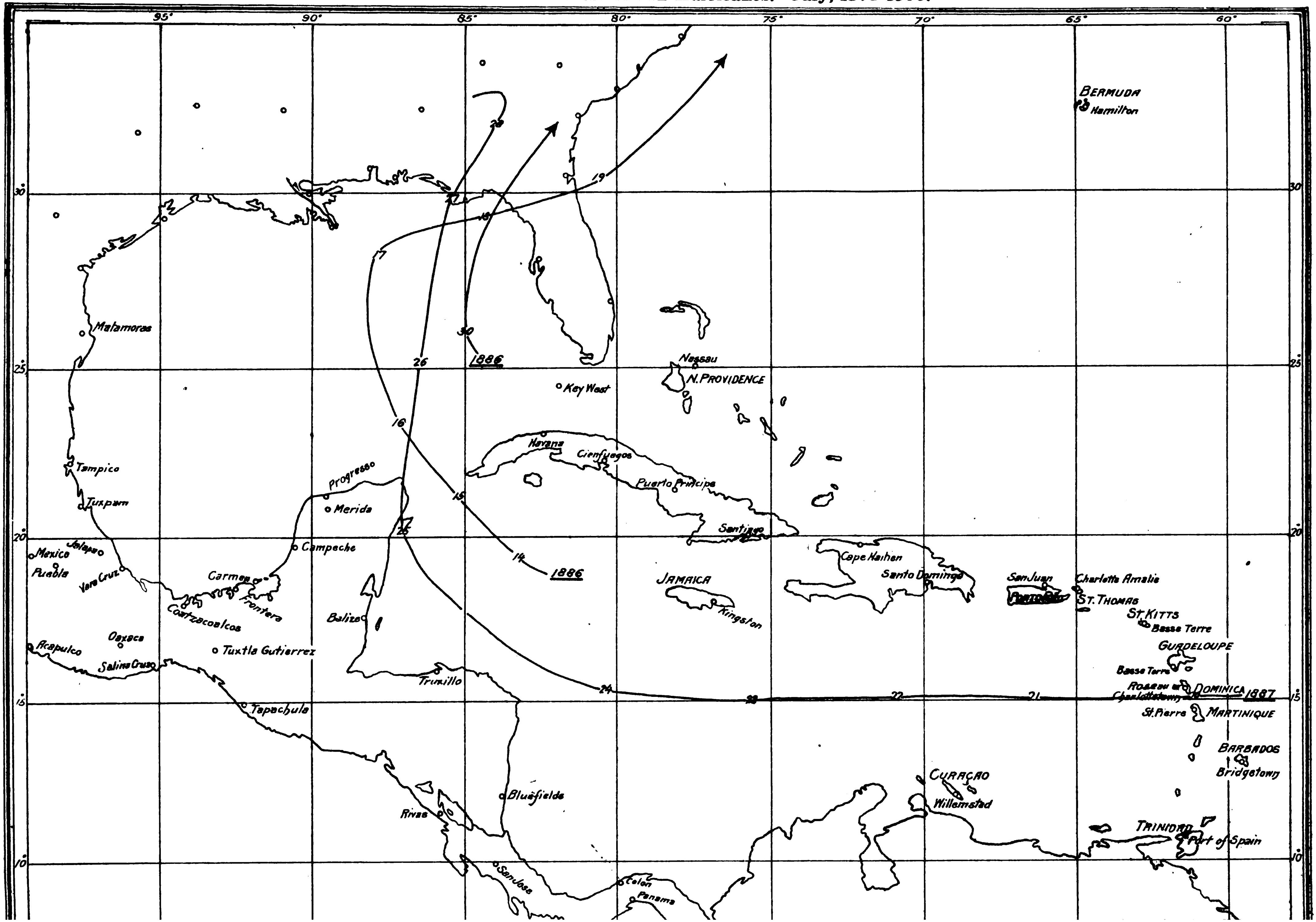


Chart IV. Tracks of West Indian Hurricanes. August, 1878-1900.

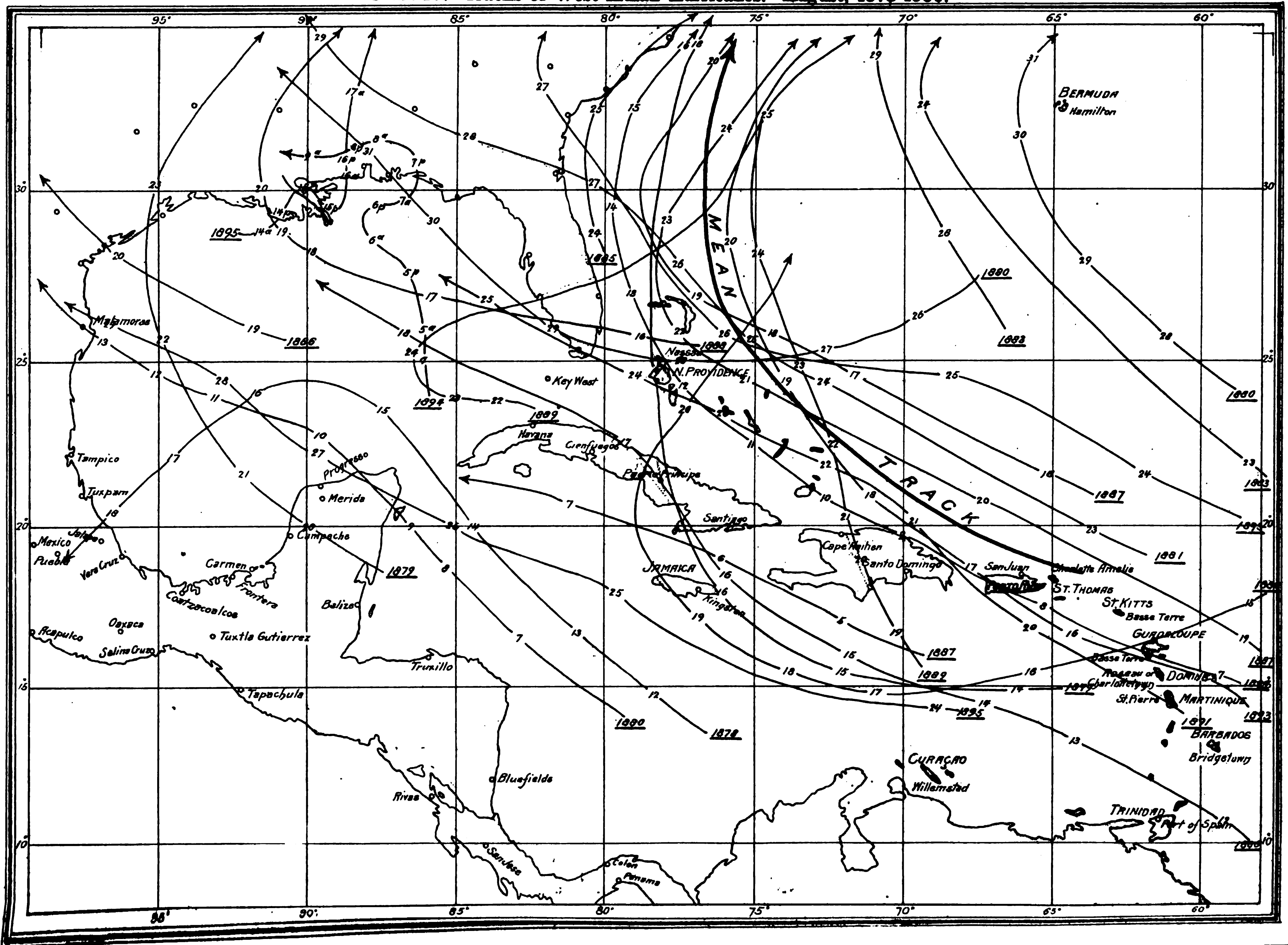


Chart V. Tracks of West Indian Hurricanes. September, 1878-1900.

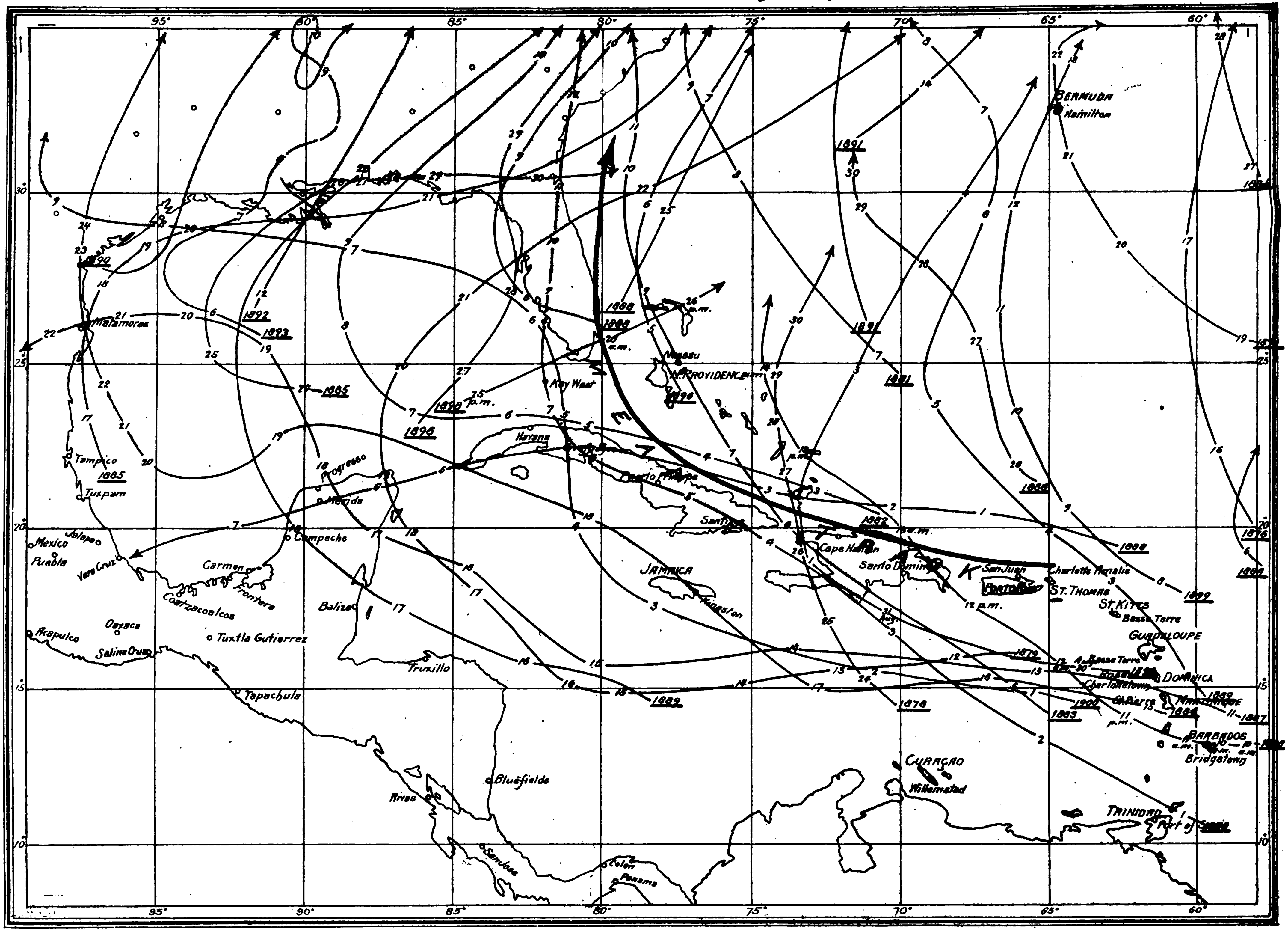


Chart VI. Tracks of West Indian Hurricanes. October, 1878-1900.

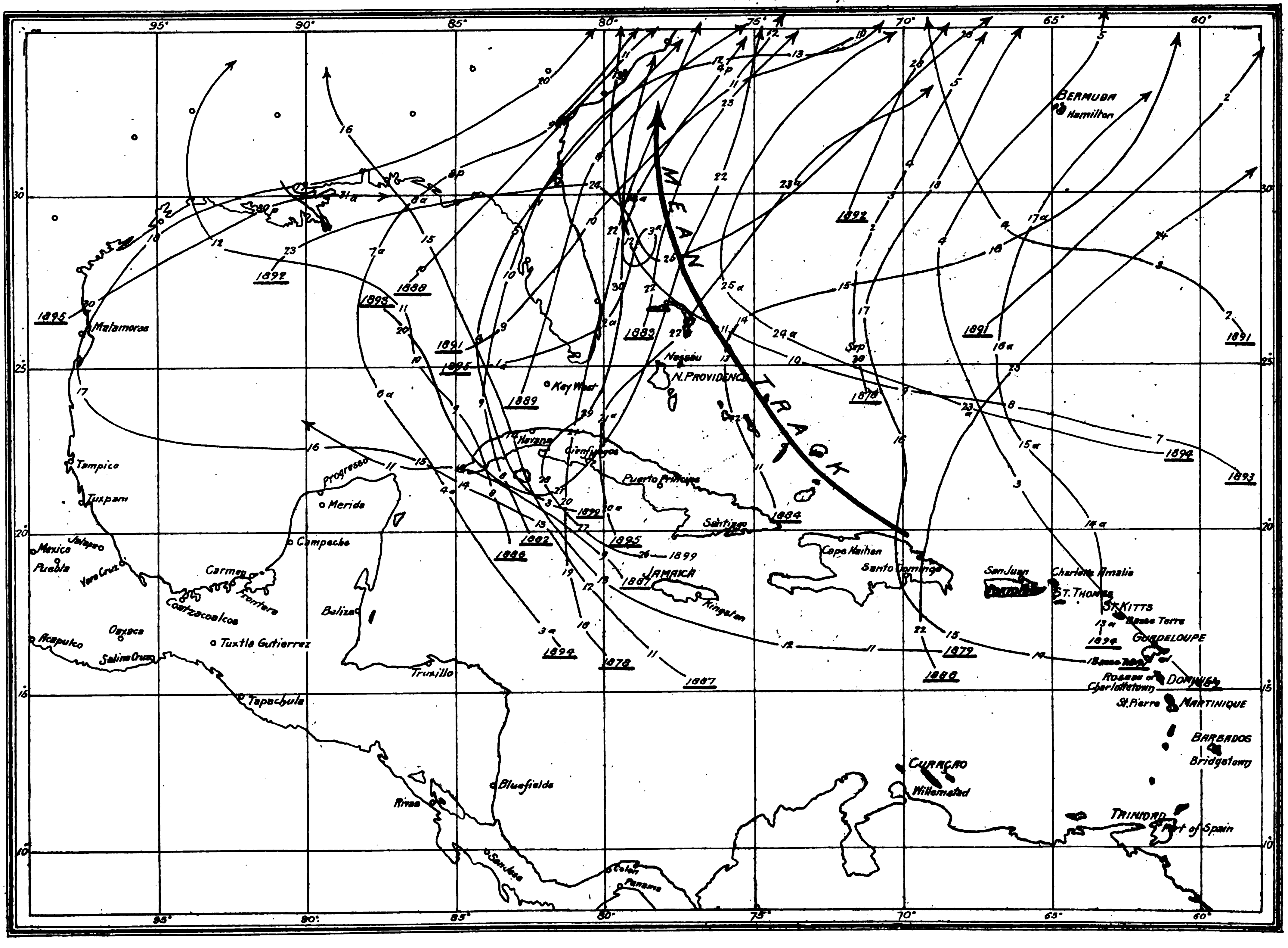
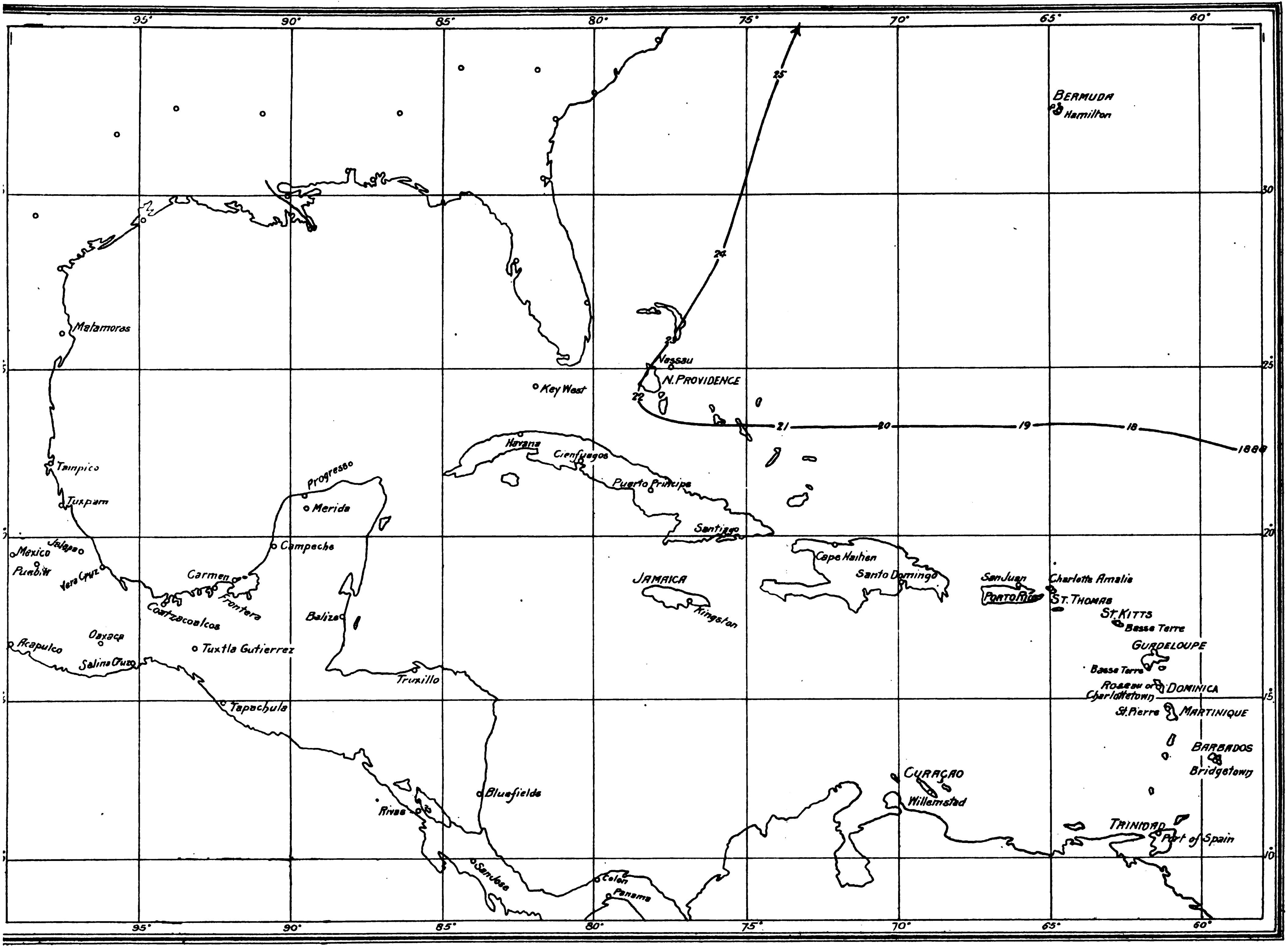


Chart VII. Tracks of West Indian Hurricanes. November, 1878-1900.



U. S. DEPARTMENT OF AGRICULTURE.
WEATHER BUREAU.

ECLIPSE METEOROLOGY AND ALLIED PROBLEMS.

PREPARED UNDER DIRECTION OF WILLIS L. MOORE, CHIEF OF WEATHER BUREAU,

BY

FRANK H. BIGELOW, M. A., L. H. D.,
PROFESSOR OF METEOROLOGY.

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LETTER OF TRANSMITTAL.

U. S. Department of Agriculture, Weather Bureau,
Washington, D. C., March 10, 1902.

Sir: I have the honor to transmit herewith a Report on Eclipse Meteorology and Allied Problems, by Prof. Frank H. Bigelow, of the Weather Bureau, and recommend that it be published as a bulletin of the Weather Bureau.

At the time of the total solar eclipse of May 28, 1900, there was much interest among scientists in several questions growing out of the effect of the moon's shadow upon the earth's atmosphere, and under my direction the Weather Bureau made some contributions to the subject by conducting special meteorological observations throughout the Southern States, and by sending a small expedition to Newberry, S. C. The result of this work, together with a discussion of allied topics, is presented by Professor Bigelow in this report.

Very respectfully,

Willis L. Moore,
Chief United States Weather Bureau.

Hon. James Wilson,
Secretary of Agriculture.

PREFACE.

The following report on the operations of the United States Weather Bureau in connection with the observations of the total eclipse of the sun, May 28, 1900, is based upon the records of the expedition to Newberry, S. C.; upon the special meteorological observations at sixty-two Weather Bureau stations located within 500 miles of the center of the track of totality; upon a considerable number of voluntary special observations executed within the belt of the umbra, in accordance with the instructions of the Washington office; and upon a study of various problems in solar and terrestrial meteorology. As the outcome of this work there have been made special studies, (1) on the apparatus planned to obtain a large-image picture of the inner corona, while yet employing a telescope of comparatively short focus; (2) on the shadow band phenomena, which appear to be due to meteorological conditions exclusively, and are not to be associated with diffraction on the edge of the moon; and (3) on the variations of the pressure, temperature, vapor tension, and wind caused by the passage of the shadow cone, together with a computation on the number of calories of heat absorbed per kilogram of air.

Furthermore, it seemed proper to extend the scope of the discussion somewhat beyond these limits for the following reasons: The recent rapid and magnificent advances in physics, especially in connection with the subject of the ionization of gases and the attendant effects in electricity and magnetism, have drawn the attention of students with renewed vigor to several problems which have for many years baffled all efforts at their solution. Thus the relations of electricity and magnetism in the sun to the production of the solar corona, and their correlated influences in the earth's atmosphere, have certainly been of late so far elucidated as to open up new lines of research, even if we have not in reality entered already upon the correct path which leads to the true solution. The range of information is very wide, and the number of papers to be examined is so great that only specialists are likely to obtain a clear idea of the status of these questions. After diligent study the conviction is much strengthened in my mind that the meteorologist stands in the best position of all to correlate the allied topics of solar physics, atmospheric electricity and magnetism, and the dynamic actions within the gaseous envelopes of both the sun and the earth. In fact the principles of meteorology embrace properly these two fields, since they are connected together by the bonds of radiation and absorption, so that the formulæ of thermodynamics and hydrodynamics have similar applications in each of them. I have heretofore shown in my other papers that the polar regions of the sun are stripped of coronal rays, and that these first appear in a collar or ruffle at some distance from the poles. But this is the exact phenomenon that results from subjecting a conducting sphere emitting cathode discharges in low-pressure gases to the action of a magnetic field, from which it is inferred that the sun acts like a magnetic body, and that the photospheric envelope is the seat of powerful electrical oscillatory discharges. It has been also found that the earth is immersed in an external magnetic field, upon which is superposed a secondary field, probably due to the action of ionization in the air, and that a term in atmospheric electricity is simultaneously produced by this cause. The diurnal variations of the atmospheric magnetic and electric fields are thus only other manifestations of the forces which cause ionization. Therefore, the conclusion can not be avoided that large interests in the study of terrestrial magnetism, as well as of atmospheric electricity, belong to the meteorologist, because part of the magnetic force is apparently produced throughout the atmosphere by the effects of solar radiation acting on its atomic and molecular constituents.

These recent researches are of primary importance to our own observers if we intend to maintain our proper place in the advancement of science. There is great danger that they will not be properly instructed in such matters unless suitable explanations of these results are placed before them. It has seemed desirable, on this account, to devote some attention to the work of exposition and review, by which at least a fair impression may be gained of the direction in which meteorology is moving, and the progress that has been already made. The belief will doubtless be strengthened in many minds that these branches of science are closely interwoven with one another, and that we can not afford to let any of these important lines of research escape our attention. A few sections of a mathematical character are added for the use of those students who seek to refresh their memory by ready references to the formulæ, and to guide others in the right course of study when they seek to seriously enter upon these problems. An effort has been made to show the connection between the MAXWELL, the J. J. THOMSON, and the HEAVISIDE systems of electric and magnetic formulæ, on account of the growing importance of the fundamental investigations which have been executed by Mr. O. HEAVISIDE.

FRANK H. BIGELOW.

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CHAPTER 1.

THE WORK OF THE UNITED STATES WEATHER BUREAU IN CONNECTION WITH THE TOTAL ECLIPSE OF THE SUN MAY 28, 1900, AT NEWBERRY, S. C.

THE WEATHER CONDITIONS.

The track of the total eclipse of the sun which occurred on May 28, 1900, passed over the Southeastern States, from New Orleans to Norfolk, as shown on Chart 1. This location of the track was very convenient for the installation of astronomical apparatus, as compared with the cases where the track crosses the unsettled districts of the earth, and it was evident that many parties would undertake scientific observations along the path indicated. Since the weather conditions are necessarily a prime factor in the procurement of valuable results, it was proper that special efforts should be made by the Weather Bureau to secure, by a preliminary survey of the meteorological conditions of the region, an approximate idea of the probable state of the sky relative to the several portions of the track. Those places which showed a special liability to cloudiness at the time of the eclipse ought to be avoided, and preference given to those which promised a clearer, purer atmosphere. In consequence of this obligation, such preparatory information was obtained by a survey of the sky during the three preceding years, and special reports on the subject were issued for the information of astronomers. It may be stated that the forecast work of the Weather Bureau was recognized in two ways: (1) The astronomical parties all selected sites within the region which was indicated by the result of the survey as likely to be the more promising; (2) the council of the Astronomical and Astrophysical Society of America passed a special resolution, which was forwarded to the Chief of the Weather Bureau, in the following terms:

> *Resolved,* That the Astronomical and Astrophysical Society of America extends to the Chief of the United States Weather Bureau its hearty thanks for his courtesy in transmitting daily weather bulletins to those astronomers who observed within the United States the total solar eclipse of May 28, 1900.

Fortunately, the weather conditions on the morning of May 28 proved to be exceptionally satisfactory throughout the track, so that very few observations which had been planned failed on account of clouds or rain. Indeed, it is very rare that such good fortune as regards weather attends so many eclipse expeditions as were located in the United States on that occasion. There was a little cloudiness and a showery condition in Georgia, but in all other places the air was clear and very quiet, the temperatures were moderate, and the pressure relatively high. To the north of the Ohio Valley and Pennsylvania there was more or less rain, and in that district the weather would have been unfavorable for observing the eclipse. The weather conditions on the morning of the eclipse—8 a. m., May 28, 1900—are shown on Chart 2. The shaded areas indicate precipitation during the preceding twelve hours.

TABLE 1.—*Path of the shadow over the United States from New Orleans, La., to Norfolk, Va.*

Number	Time		Northern limit of shadow path		Central line		Southern limit of shadow path		Duration of totality on the central line
	Greenwich mean time	Local mean time (a. m.)	Latitude	Longitude	Latitude	Longitude	Latitude	Longitude	
	d *h* *m*	*h* *m*	° ′	° ′	° ′	° ′	° ′	° ′	*m* *s*
1	May 28 1 30	7 27.4	+29 56.3	91 5.1	+20 46.5	90 39.7	+29 36.7	90 14.3	1 12.6
2	1 35	7 47.1	31 47.7	87 22.8	31 36.0	86 58.2	31 24.3	86 33.6	1 19.6
3	1 40	8 5.2	33 25.0	84 5.2	33 11.8	83 41.4	32 58.6	83 17.6	1 26.0
4	1 45	8 22.2	34 51.9	81 4.1	34 37.3	80 41.1	34 22.7	80 18.1	1 31.7
5	1 50	8 39.5	36 10.3	78 14.6	35 54.4	77 52.4	35 38.5	77 30.2	1 37.0
6	1 55	8 54.2	37 21.7	75 33.5	37 4.6	75 12.1	36 47.5	74 50.7	1 41.9

Table 1 gives the location of the path, the times of the occurrence, and the duration of the totality on the central line at the six places marked by lines crossing the track, as shown on Chart 1. It states that the duration of the totality increases from about 72 seconds near New Orleans to about 100 seconds near Norfolk, and this would suggest a choice of locality for the eclipse stations as far eastward as possible.

The results of the observations on cloudiness were published in three reports for 1897, 1898, and 1899, and the summary of them is contained in Table 2. This records the fact that each of the three years testifies that a minimum of cloudiness should be found in Georgia and South Carolina, and a maximum near the Atlantic and also near the Gulf coasts. Accordingly, one would prefer a site on the high land of the Appalachian range, and in consequence avoid the Norfolk district. This brought up a conflict of interests, since there was a gain of time by going eastward, but an increase of risk from cloudiness, and hence a compromise of some sort was necessary. The stations actually occupied by the large observing parties are shown on Chart 1, and it indicates that astronomers preferred to sacrifice a few seconds of time rather than take the chances of observing in the hazy conditions likely to prevail in the low country adjoining the ocean. Newberry, in South Carolina, just to the northwest of Columbia, was selected by the Weather Bureau party, whose work is described in this report.

TABLE 2.—*Summary of the meteorological results for three years, 1897, 1898, 1899.*

[The figures are percentages of cloudiness.]

State	1897		1898		1899		Means	
	General sky	Near sun	General sky	Near sun	General sky	Near sun	General sky	Near sun
Virginia	....	....	44.9	41.7	35.7	34.3	40.3	38.0
North Carolina	35.8	33.3	28.2	25.7	33.3	30.6	32.4	29.9
South Carolina	33.7	32.1	17.5	16.0	28.1	26.7	26.4	24.9
Georgia	18.4	16.0	12.2	10.8	18.5	17.4	16.4	14.7
Alabama	15.2	14.9	17.1	15.7	22.4	22.6	18.2	17.7
Mississippi	....	....	23.0	26.4	38.6	31.9	30.8	29.2
Louisiana	26.5	21.5	36.4	30.9	35.9	30.6	32.9	27.7

CHART 1. **Track in the United States of the Total Eclipse of May 28, 1900.**

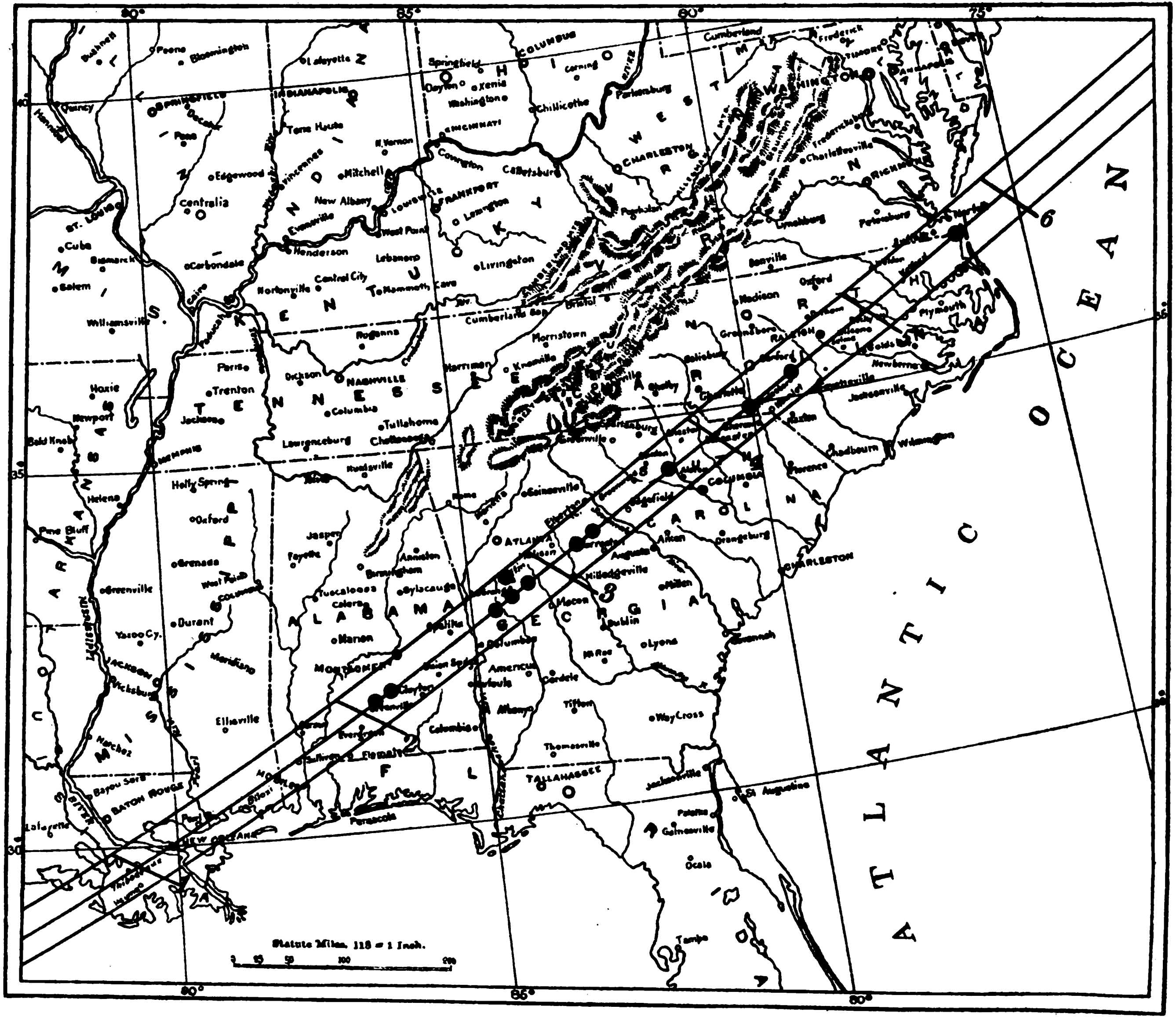
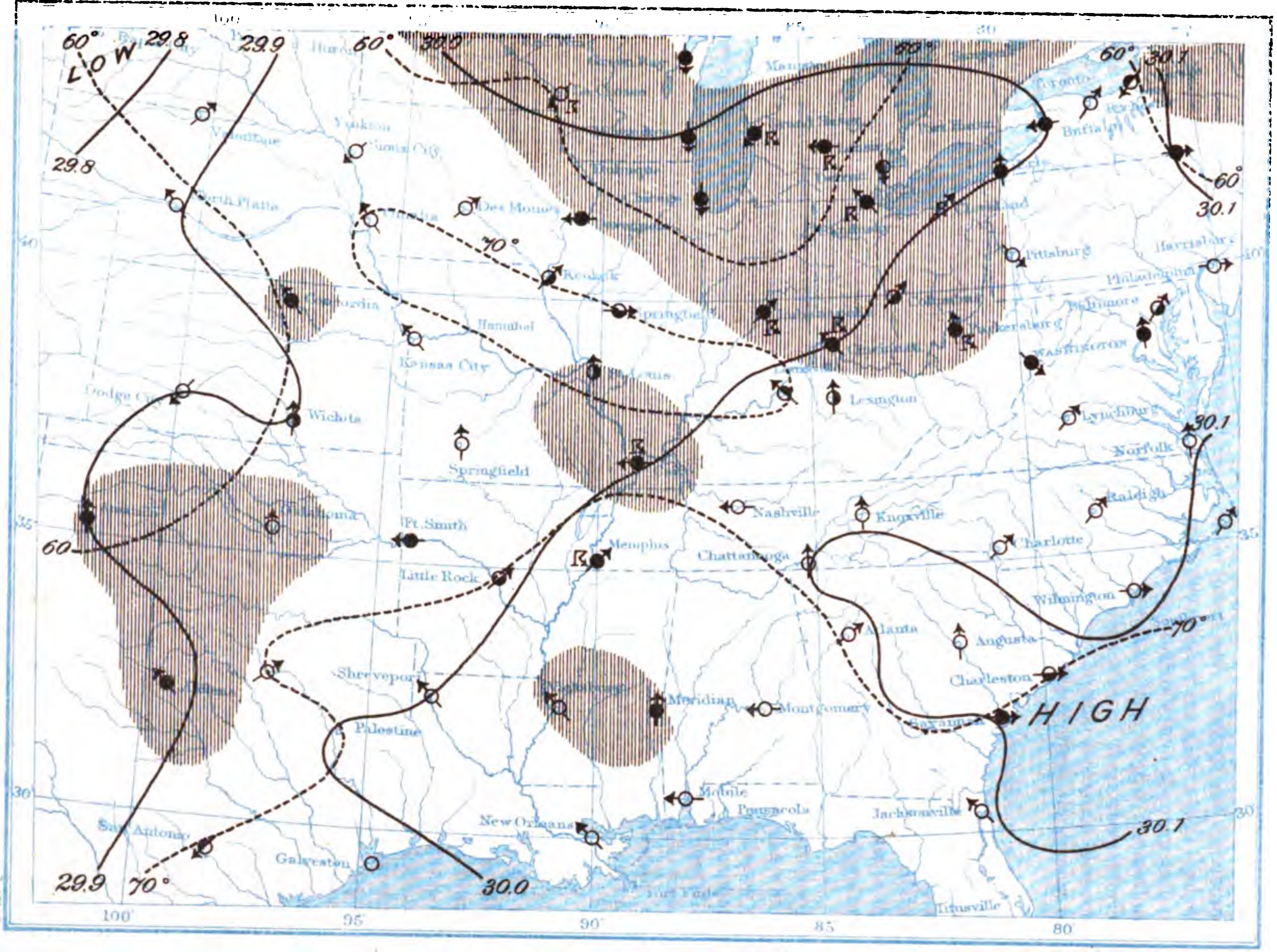


CHART 2. Weather map showing the conditions at 8 a. m., May 28, 1900.



OBSERVATIONS FOR THE METEOROLOGICAL EFFECTS AND THE SHADOW BANDS.

Further preliminary work was done by the Weather Bureau in two directions.

(1) For the observations on the effect of the passage of the moon's shadow upon the pressure, temperature, and vapor tension of the atmosphere, suitable forms were prepared and distributed to the regular stations of the Weather Bureau located within 500 miles of the moon's total shadow. Fortunately several first-class meteorological observatories were situated within the very path of totality, so that it was not necessary to make any further preparations than to give instructions regarding the reading of the instruments. An account of the discussion of these observatories is to be found in Chapter 2 of this report, where it is shown that the meteorological elements were appreciably affected, and that from the variations it is possible to compute the amount of the heat lost or gained per kilogram of air.

(2) For the observations of the shadow bands a circular was prepared, describing a simple method of observing them, which was distributed along the belt of the path of totality to our regular and volunteer observers, giving them sufficient time before May 28 to admit of all the necessary preparations being made. A full account of the results of this work will be found in Chapter 3. The principal purpose was to decide whether the shadow bands are a diffraction phenomenon, due to the action of the moon's edge on the solar light, or a phenomenon in the earth's atmosphere, and thus strictly a meteorological effect. It seems that the observations are decisive in favor of the latter hypothesis.

Finally the view of the corona, which was obtained at Newberry, S. C., and our studies in the subject of solar physics, suggested the idea of reviewing the recent advances in physics which have a direct bearing upon the meteorological problems, especially those of the transmission of solar energy to the earth's atmosphere and the transformation of this energy within the atmosphere itself. A brief summary of these studies is contained in Chapter 4, and it will be found useful in showing to meteorologists and astronomers generally the status of these important topics, which are now claiming to an unusual degree the attention of physicists. A condensed summary of certain systems of formulæ is also added in Chapter 5, which will be convenient for reference by advanced students in these fields of astrophysical research.

PERSONNEL OF THE EXPEDITION.

By direction of the Chief of the Weather Bureau, I proceeded from Washington, D. C., to Newberry, S. C., on May 22, for the purpose of installing the apparatus. I was joined on May 26 by Prof. CLEVELAND ABBE, whose report on the polarization of the sky will be found elsewhere. Mr. ROBERDEAU BUCHANAN, of the Nautical Almanac Office, Prof. WALTER S. HARSHMAN, of the United States Naval Observatory, Mr. JAMES PAGE, of the United States Hydrographic Office, Mrs. BIGELOW, Mrs. BUCHANAN, the Misses WILKES, Miss LINDSLY, Mrs. HARSHMAN, all of Washington, took the opportunity to view the phenomenon of the eclipse. Prof. GARRETT P. SERVISS, Mr. OTIS WATTLES, Mr. CHARLES LEMBKE, Mr. WALLACE GOOLD LEVISON, of Brooklyn, N. Y., also made observations in Newberry. We received ready hospitality and practical assistance from President GEORGE B. COMERS of Newberry College, from Professors SLEIGH and CANNON, from Dr. HOUSEAL, on whose grounds the Weather Bureau apparatus was located, from Mr. W. T. DAVIS, who supplied the masonry and carpenter work, and from Mr. J. Z. SALTER, who placed his photographic laboratory at our disposal and assisted in taking and developing the photographs. The proprietors of the Newberry House and the superintendent of the Newberry cotton mill also performed several acts of courtesy which were much appreciated. The local press was pleased to record our work, and the citizens of the city assembled one evening to listen to brief lectures on meteorological and eclipse topics by Professors ABBE and BIGELOW. Similar lectures were given at Columbia, S. C., at Rockhill, S. C., and at Charlotte, N. C. In all of these places it was noted that the work of the Weather Bureau seemed to be regarded with much favor, and a growing appreciation of the value of the service was generally pronounced to be the result of the outcome of local experiences. We were indebted on these occasions to the cooperation of Mr. J. W. BAUER, section director at Columbia,

S. C., to Prof. **Cleveland Abbe**, Jr., of the Winthrop Institute, Rockhill, S. C., and to Mr. **John Wilkes**, of Charlotte, N. C. The Southern Railroad also made special arrangements for our accommodation. Our thanks are hereby extended to all those persons who thus contributed to make the expedition pleasant and successful.

THE LOCAL CIRCUMSTANCES AT NEWBERRY, S. C.

The local astronomical circumstances at Newberry were as follows:

Latitude	34°	16′	
Longitude	81°	39′	
	5^h	26^m	36^s
Sun's declination	21°	26′	
Eclipse begins civil G. M. T.	13^h	43^m	
Local M. T.	8^h	$16^m.4$	
75th meridian time	8^h	43^m	

The location of our instruments was about 2 miles north of the central line of totality. The weather was perfectly clear, the sky nearly free from dust and mist, the air was calm with a wind velocity of only 2 or 3 miles per hour, and apparently quiet to great altitudes. This was due to the facts that Newberry is in the midst of the prevailing high-pressure belt, where the west-east circulation is a minimum, and that the pressure conditions were normal on the morning of May 28 when the western portions of the south Atlantic high overspread the Southeastern States. The air was dry and a temperature of 68° F. prevailed at the beginning of the eclipse, falling to 64° a quarter of an hour after totality. No special effort was made to make meteorological observations at Newberry, because these were provided for suitably at other places, and there seemed to be no reason for adding to those records. The wind fell to a dead calm at the time of totality, and the smoke of the neighboring city ascended nearly vertically. On the preceding days it had been drifting quite vigorously in various directions.

THE PURPOSE OF THE NEWBERRY OBSERVATIONS.

The writer of this report was a member of the United States Eclipse Expedition, which was sent to Cape Ledo, West Africa, to observe the eclipse of December 22, 1889, and it was natural that the experiences of that occasion should suggest the line of work undertaken for May 28, 1900. My duties in connection with the Weather Bureau rendered it impracticable to enter upon as extensive astronomical preparations as would have been desirable, and there was no expectation of being able, with the instrument in my possession, of competing with the magnificent photographs obtained by specialists engaged in astrophysical researches. Indeed, it is becoming plainer every year that the day of the amateur observer of eclipses is passing away, and that the expert knowledge and practice required for the preparation of suitable eclipse apparatus and photographic material can be acquired only by those who devote much time to this class of investigation. Nevertheless, in the development of ideas there is always some preliminary experimenting to be done, and it was on this modest plan that our work was conceived and executed. Its results may be sufficiently suggestive to constitute a proper contribution to the literature of the eclipse.

Photographs of solar eclipses may be divided into two classes: (1) Those which seek to obtain the total effect of the corona, extending continuously from the photosphere of the sun outward into space as far as it is possible to trace it. Such results are obtained by using a plate in the focus of the telescope, whereby all available light is concentrated from the objective on the sensitized film. If long streamers are to be obtained, the disk of the moon covering the sun must be on a small scale, and a telescope having a focal length of 8 or 10 feet, which makes an image of the sun approximately one-half an inch in diameter, is, perhaps, the most successful, though excellent photographs of the details of the outer corona have been made on even a smaller scale than that. (2) On the other hand, if one wants the minute structural details of the inner corona, then it is necessary to enlarge the image of the sun up to 4 inches in diameter and as much more as is practicable. To do this requires a long focus, as, for example, 40 feet for a

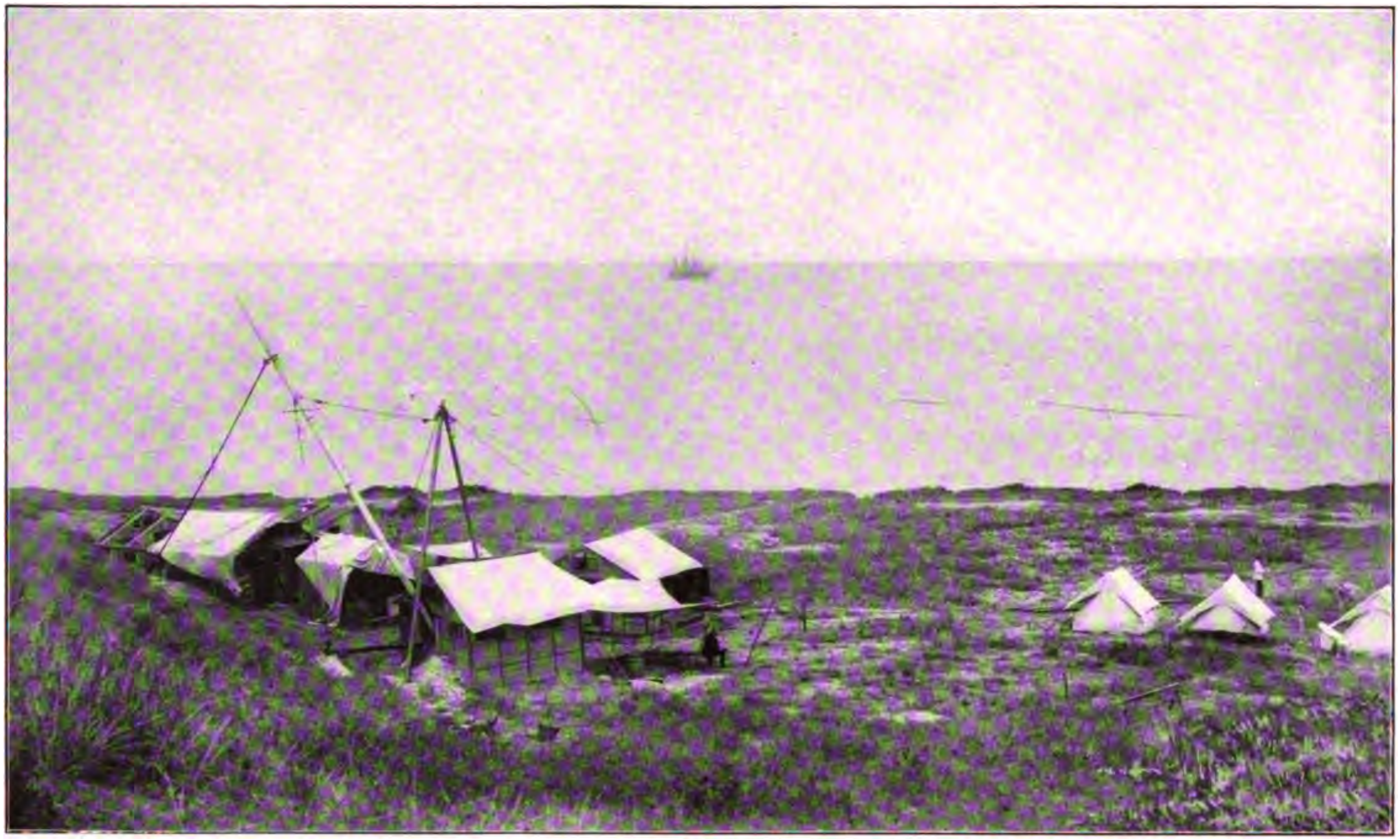


CHART 3.—CAMP OF THE UNITED STATES EXPEDITION, CAPE LEDO, WEST AFRICA, DECEMBER 22, 1889.

4-inch image on the photographic plate. During the eclipse of May 28 a lens having a focal length of 135 feet was operated by the party of the Smithsonian Institution, which gave a very large picture and minute details of all kinds. The employment of these long telescopes in the field, especially in a rough country, is unfortunately no easy task, and in fact the cost and labor of transporting and installing such apparatus is a serious consideration. Furthermore, if the auxiliary apparatus of reflecting mirrors with the necessary clockwork is to be established in distant countries, the entire task is such as to limit this class of operations to a very few persons.

METHODS OF MOUNTING LONG-FOCUS LENSES.

There are two methods of mounting these long focal lenses in the field, first by keeping the axis parallel to the ground, second by mounting it in the air with the axis pointing to the sun during the eclipse. As the sun moves along its path it is evident that if the position of the lens is fixed there must be constructed a counter motion at the focal plane. This has been done by mounting the photographic plate on a movable track, whose position is carefully calculated beforehand. If the axis is parallel to the ground this is comparatively simple. If it is pointing skyward the position of the track is not so easy a matter to locate. If one uses a siderostat to reflect the rays of a moving sun into the lens and thence to the plate, there is a twisting motion of the rays on the plate which blurs and distorts the image if the exposure is not very short. This disturbing action will blot out all fine details if the exposure is of considerable length, such as is requisite to get the details of the corona outside of the brilliant inner corona. If the lens is mounted in the air there are two ways of compensating the sun's motion, and these avoid the distortion entirely, which is an important consideration. The lens may be placed in a tube which holds at the lower end the camera fixed to it, while the tube swings to follow the sun; or the lens may be placed on a staging and connected with a camera by means of a large tube sufficiently wide to allow for the motion of the sun's image during the time of the totality. There is much trouble in providing for the lofty stage, as it involves the use of much lumber, a large amount of canvas, a good clepsydra or other form of moving apparatus, which shall operate with much perfection in order to keep mechanical tremors out of the photograph. The action of wind and weather on the canvas tube may also easily spoil the result unless the day is very favorable. However, good pictures have been obtained by both methods, as by Schaeberle in Chile, 1893, Campbell in India, 1898, and by two of the United States parties in 1900. The Chile eclipse was observed with the horizontal and the others with the skyward axis. The important consideration is to get results, but it is also desirable to secure them with the minimum of labor and risk from tremors produced by the wind and by mechanical movements. The ideal condition is evidently to be found in a combination where a lens of long focus is attached to a tube which carries the camera, and moves as one body like an equatorial telescope under the operation of suitable driving power. The first attempt to accomplish this object was made by the writer at Cape Ledo in 1889, where a 40-foot lens was mounted in a tube and pointed skyward.

THE 40-FOOT TUBE WITH DIRECT AXIS AT CAPE LEDO.

Chart 3 shows our camp with the 40-foot tube in the foreground. The ship in the offing is the old man-of-war, the *Pensacola*, Captain Yates, which carried the expedition. The latitude of Cape Ledo is about 12° south, so that a slight inclination of the polar axis on sloping ground was easily attained. The axis was attached to two heavy bases firmly set into the ground. Evidently rotation about a line parallel to the base will follow sidereal motions. This was accomplished by attaching the tube, near one end, to ball connections which gave free motion in all directions. The supporting rod was such as to make the angle of elevation of the tube correspond with the declination of the sun on the day of observation. The upper end of the declination rod was provided with motion in one direction only, to allow the change in the angle of elevation to be made; and the length of the rod was adjustable by an extension buckle near the lower end, of sufficient strength to be firm, and to admit of setting of the axis of the lens accurately by turning it through the required angle. The base was made of 6-inch gas pipe, the tube of 8-inch thin sheet steel, and the supporting rods of 2-inch gas piping, the tube and declination rods being stiffened by systems of bracing rods. The lower end of the tube projected about 2 feet into a dark camera room, through an opening in a house covered with two or three thicknesses of heavy dark canton flannel, and it carried the photographing apparatus which has been described in Astronomy and Astrophysics for April, 1892. The motion of the tube in hour angle was governed by a rod attached to the tube by a ball connection and resting on dry sand in a heavy piston 3 feet long. The sand was drawn off by a special valve, which could be made to regulate the speed by turning a screw so that the fall should be equal to that of the sun. A pair of poles was erected in connection with a rope and pulleys for taking up the weight of the apparatus in preliminary work. We had sufficient help from the *Pensacola* at our disposal, so that it was practicable to employ these methods on that occasion. The hour-angle rod was made in several parts which fitted together, so that the tube could be used near the meridian or down toward the horizon. It is evident that adjustments in azimuth were readily made by following the sun from noon to near sundown, and taking up the variation by altering one end of the base at the anchor irons. Aside from distribution of the weight of the instrument, we have all the essentials of an equatorial telescope of special solidity and stability, since the lower end was held in a grip of iron near the camera and the upper end was braced on a tripod having a spread of 10 feet one way along the polar base, and 30 or 40 feet in both the other directions. As to results, it was found that the definition and steadiness of the sun's image in the dark room was all that could be desired, and that the pictures of the cusps of the sun taken through clouds at the beginning and ending of the eclipse were very satisfactory, promising an admirable performance on the corona. Unfortunately the clouds thickened at the time of the totality and entirely blotted out the corona. The weather had been very good for several afternoons preceding the 22d; but there is every reason to think that it was the presence of the shadow near the seacoast and the accompanying chill which was sufficient to condense the vapor in an atmosphere already at a high relative humidity.

Having this experience and these principles in mind, I was anxious to see how far they could be adapted to use in a short telescope, and at the same time secure a large image of the sun with the surrounding coronal appendage. For it is very evident that a small apparatus producing similar results would be more practicable in field work than the large 40-foot combination used at Cape Ledo. I had at my disposal only a small refractor uncompensated for the photographic rays, 4½ inches aperture and 48 inches focal length, and accordingly my pictures are of little value beyond being a criterion for some important experiments of which others may take advantage. However, it is my conviction that a short-focus apparatus arranged for an enlarged image will become the last product of the evolution of eclipse photographic telescopes.

THE MOUNTING OF A SHORT-FOCUS TELESCOPE FOR ENLARGED IMAGE, AT NEWBERRY, S. C.

The following apparatus was constructed at the Weather Bureau and mounted at Newberry, as shown on Chart 4. Heavy 8-inch posts were sunk in the ground about 4 feet and embedded in broken brick and Portland cement; about 2 feet above the surface they were sawn off in a horizontal plane, as determined by leveling; on this was laid a plank about 6 feet long, with the central line in the geographical meridian; it was clamped to the posts by heavy iron bolts, which, passing through slots in the board, admitted a moderate amount of adjustment in azimuth; over the posts was erected at one end an iron stand to carry the northern end of the polar axis near the telescope; over the southern post was erected a foot iron which admitted an adjustment of the foot-end of the polar axis through several degrees in polar distance, and thus would allow stations having several degrees of difference in latitude to be occupied by the same instrument on different occasions; an extension rod in declination with a turn buckle permitted the adjustment in declination. On Chart 4 is seen the plan of the mounting.

A = the posts sunk in the ground.
B = the horizontal board.
C = the connecting bolts with azimuth adjustments.
D = the polar axis.
E = the northern support.
F = the southern support with adjustment in latitude.

G = the rotation axis with clamp.
H = the rotation foot with bearing.
I = the declination rod with extension buckle.

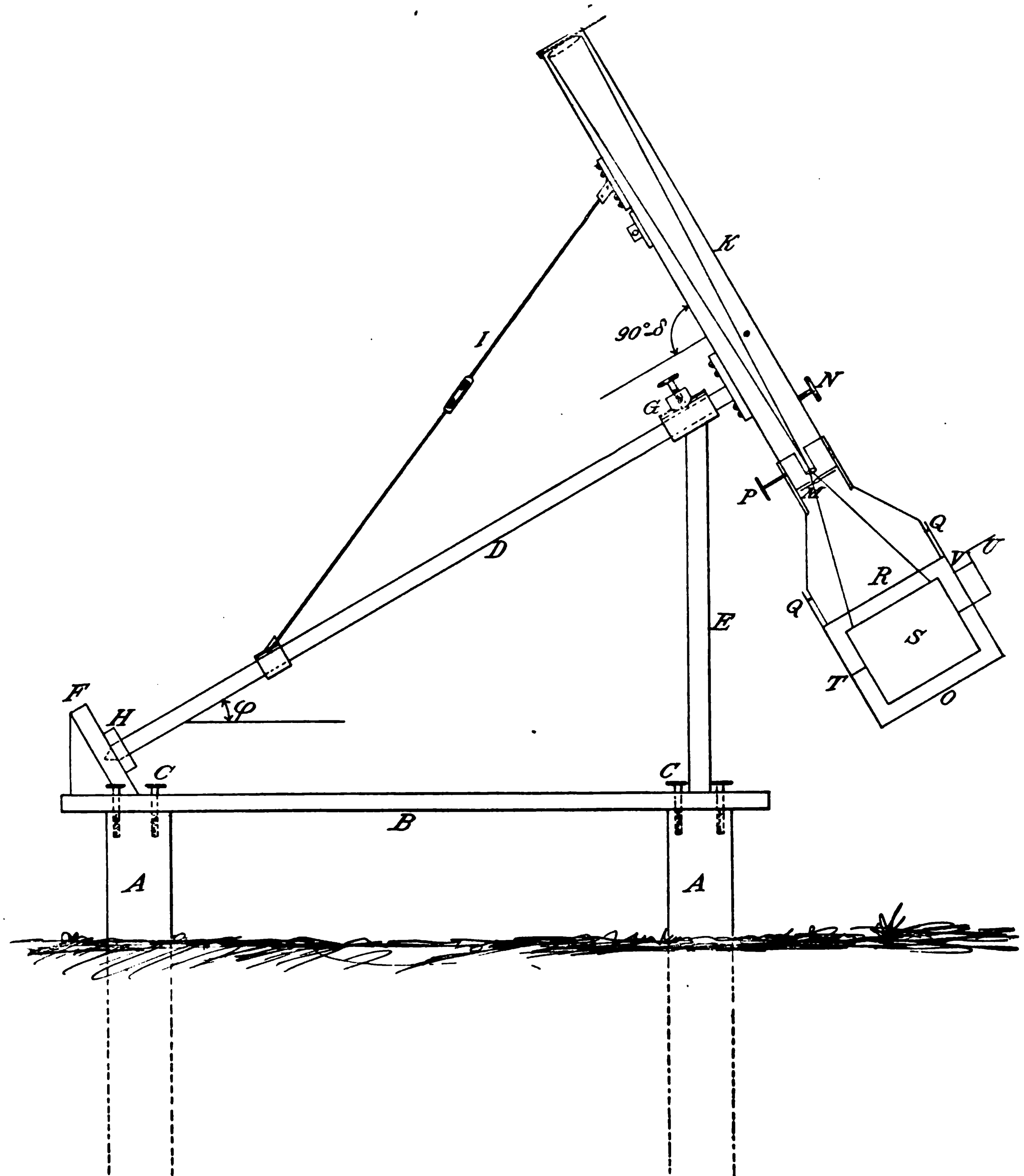


CHART 4.—Mounting of a short-focus telescope for enlarged image, at Newberry, S. C.

Hence, by measuring from the horizontal plane the angle $\varphi=34^\circ$ 16′ for Newberry, S. C., and the angle $90^\circ-\delta=68^\circ$ 34′ for May 28, we place the axis of the telescope in the plane of the sun for that date. I succeeded in setting the sun upon the plate of the camera at the first rough adjustment, and could center it perfectly by means of the turn-buckle I.

THE CAMERA APPARATUS.

The telescope itself was first inclosed in a square wooden box *K*, just large enough to receive it, as a foundation for the attachment of all required auxiliary apparatus. Upon this was screwed the irons *D* and *I* by appropriate joints. The wooden tube was a little longer than the telescope; upon the upper end was placed a shutter slide *L*, made of a thin copper sheet running in grooves; the lower end was stopped by a block of wood, pierced by a hole large enough to carry the emerging pencil of light, and this was covered by a second aluminum shutter *M*, by which the exposures were made. It ran by the central hole to the blank pieces at each end, and it was drawn across quickly for short exposures, as required. The shutter *L* when closed permitted manipulations at the camera; when *L* was open the shutter *M* alone controlled the exposures; by means of the two entire safety from the external light with speed of operation was always secured. The focusing screw *N* controlled the fine adjustment of the image on the plate. The camera *O* was made in two parts, as it was proposed to operate in the open air, outside of a dark room. A trumpet-shaped connecting piece slid at one end over the telescope box, and thus permitted the large adjustments of the focal plane to be made by slipping it along the tube, after which it was clamped with the screw *P;* the other end opened wide to about 11 inches and then had a short extension parallel to the telescope tube. This carried on two of its sides some brass runners, matching slots *QQ* on the camera box proper. The purpose of this arrangement was to detach the camera entirely from the tube, so that it could be taken away. The camera, therefore, had a closing shutter *R* which when down rendered the plate chamber light-tight, and when drawn up permitted the light to pass into it upon the plate. This chamber contained a square frame *S*, carefully made to hold four 8½ by 6½ plates, which was centered on the axis *T* carrying a handle *U* on one end. By turning the handle to four different points, and fixing it to them in succession by a spring and V-point, the plates were mechanically placed in the focal plane of the telescope. An enlargement of 36 diameters was used, the eyepiece being furnished by G. N. SAEGMULLER, of Washington, D. C. The camera was loaded with the plates in a dark room and the shutter *R* closed; it was then carried to the telescope and placed on the slides *Q*. On drawing the shutter *R* all was ready to operate, by first drawing *L* and then exposing through *M*. This worked on a spring back and forth, and on driving it in one direction a plate was exposed; then *U* was turned to the next hole, at right angles to its first position, and the second exposure was made. This mode of working causes the least possible loss of time for changing the plates, the minimum of jarring, and permits a very perfect regulation of the length of the exposures, from a fraction of a second to any required interval. A second camera was prepared, so that by removing the first and substituting the second, with the loss of a very few seconds another set of four plates was ready for exposure.

The advantage accruing to the exposure of a photographic plate in the focus of a long lens, without any enlargement, is due to the fact that the entire available light is concentrated. The disadvantage is that in the case of the corona the contrast of light is so great between the inner coronal ring and the thin outlying streamers that the inner structure is entirely lost in a general blur on the plate, while the outer rays do not come down at all. In consequence, these large scale pictures, while beautiful, are very featureless. They show the prominences and the average distribution of actinic material, but the coronal details are usually sacrificed. Now, one way to overcome this difficulty in part is to spread out the coronal image by an enlarging lens, and give the exposure more time, to compensate for the thinness of the light. This tends to form the detailed structure much more minutely, and it is my belief that this principle is the proper one to employ in developing the eclipse telescope. On the other hand, an increase in the time of the exposure brings in its train other difficulties to overcome. For a 1-second exposure a clock motion is a subordinate matter, but for one of 10 to 15 seconds it is of primary importance; also, the liability to tremor in the telescope, due to gusts of wind and other causes, renders it imperative that the motion should be communicated in a manner contributing to steadiness and rigidity. The ordinary equatorial mounting, where the telescope is balanced at the center and the driving motion is communicated through a small wheel, is far from being adequate to these requirements. There must be a special device for moving the telescope in hour angle and at the

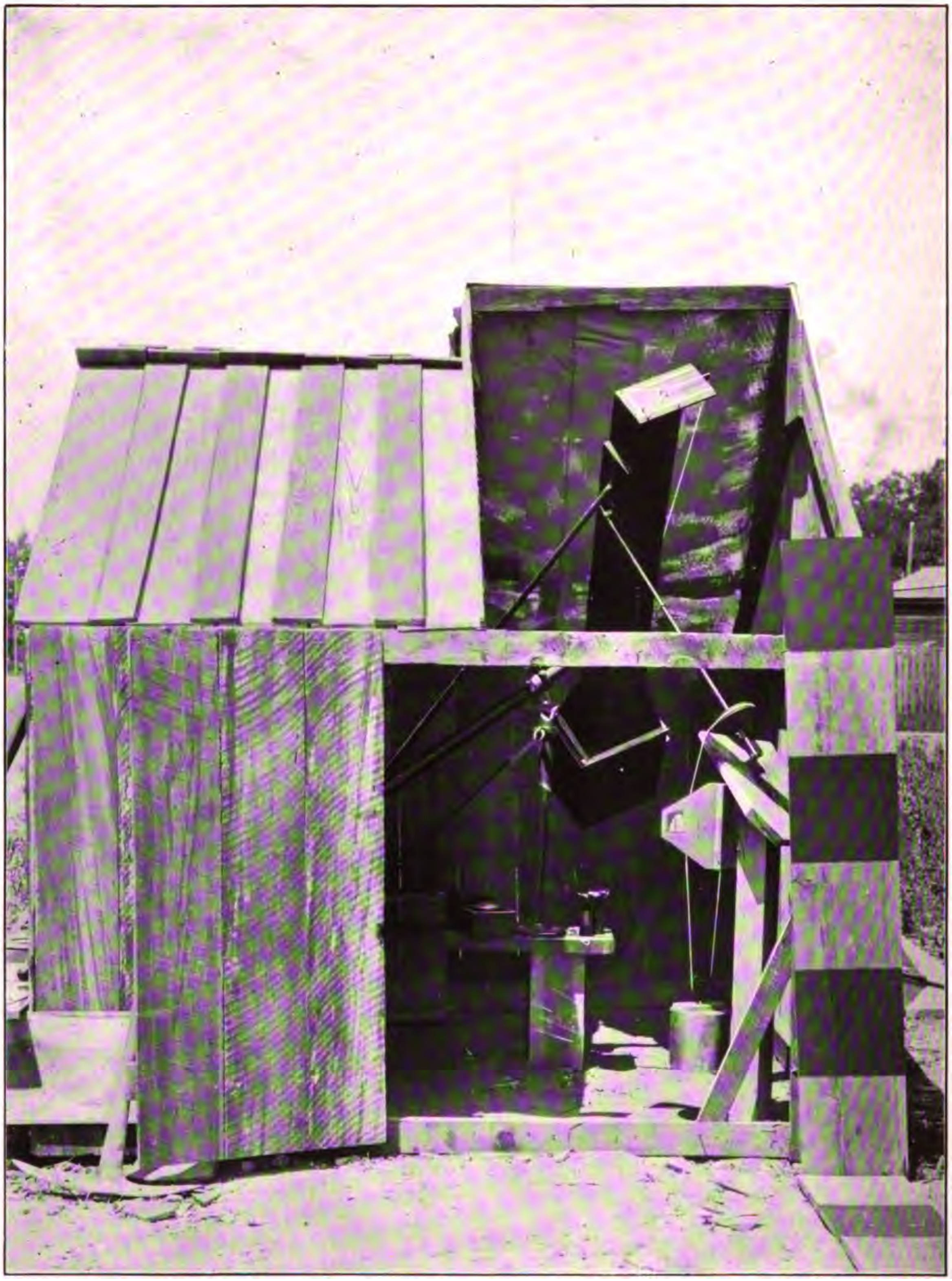


CHART 6.—THE OBSERVER'S HOUSE AT NEWBERRY, S. C., SHOWING THE POSITION OF THE TELESCOPE AND THE AUXILIARY APPARATUS.

same time holding it firmly at every point. The apparatus just described is suitable to secure a true setting and to follow the sun at any hour of the day. What is needed in addition is a short differential time motion lasting through the critical moments of the totality.

THE MOTION IN HOUR ANGLE.

This was secured as follows: The essential features are a rod stretching from the top of a long post, set firmly with cement in the ground, to the upper end of the telescope tube, as shown on Chart 5, or Chart 6. Let the post A carry a board B inclined at an angle that will be nearly parallel to the direction of the driving rod at the moment of totality. The rod C extends from the plate B to the tube D; at the lower end it terminates in a firm standard, made to move in two planes at right angles to each other, so as to prevent any frictional binding; the upper end runs through a similar two-way standard, and terminates in a good screw for giving the slow motion; it can be readily taken out by a movable clamp cap. This is convenient for quick approximate

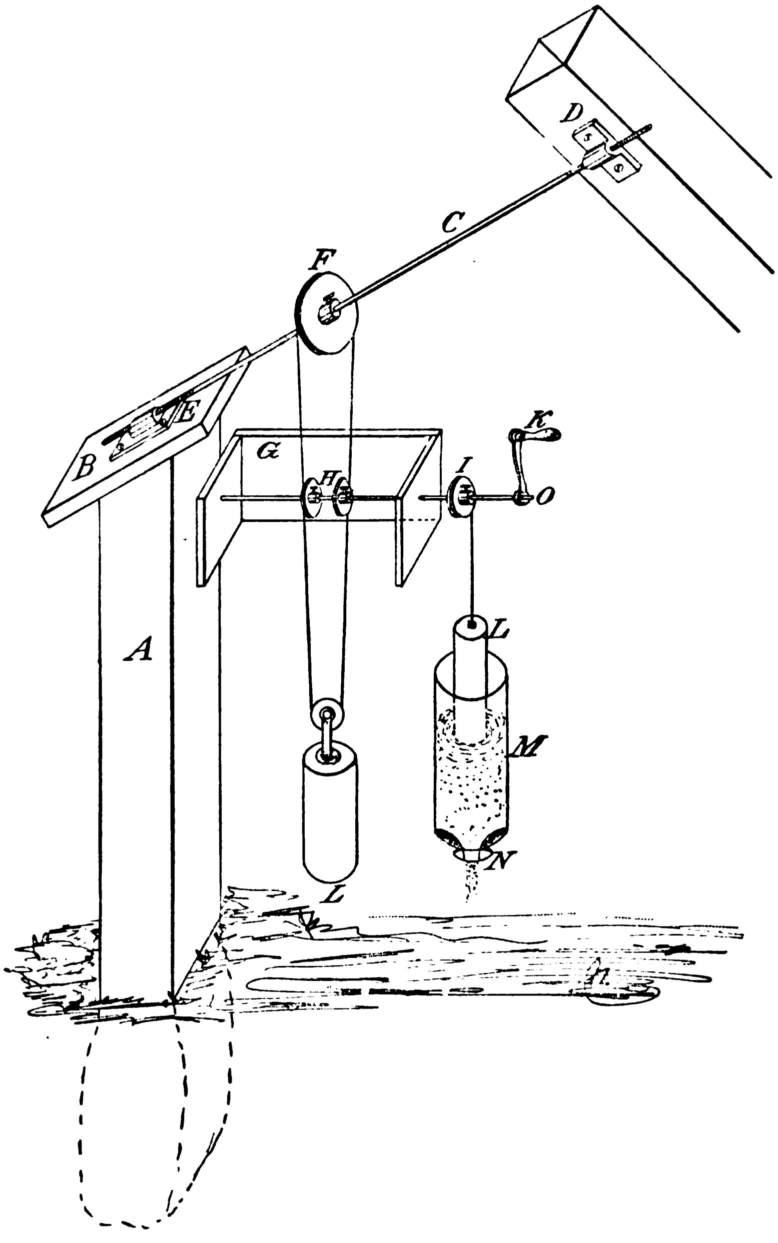


CHART 5.—The apparatus for the movement in hour angle.

adjustment, and for removing the rod entirely from the telescope. The rod carries a grooved wooden wheel *F*, which is adjustable to any position on the rod by a brass hub carrying a set screw. The post also has a frame attached to it on one side; through the center of the frame runs an axle which carries two small wheels *H*, both adjustable along the axis by clamp-screw hubs; outside the frame this axle carries a small wheel *I*, and a turning handle *K*: an endless cord is now wound over *F* and *HH*, and continues to a stretching weight *L*, which keeps it taut. Upon *I* is wound a cord which is attached to a piston weight *L*; this rests upon sand in a piston *M*, and the flow of the sand is regulated by the conical valve *N*. The wheel *I* is clamped to the axle *O* by a clamp thumbscrew, so that it can be detached readily or set in the proper place when the weight *L* is needed for working. The handle *K* is useful for quick motion, and for preliminary experimental work. Indeed, a skillful hand on the handle *K* is sufficient for imparting a very steady motion to the telescope tube, by making so many turns per minute. Of course the dimensions are all relative and depend upon the telescope. Any form of driving the rod *F* may be substituted for this contrivance, as a good clockwork on the other side of the post *A*, operating directly upon the rod *DB* extending beyond the inclined plate. The essential feature is that the bearings at *E* and *D* should be firm, and as frictionless as good workmanship can secure, all the other parts being of secondary importance. This rod also supports the telescope at its upper end, and guards it against all vibrations from the wind; also, it stops very quickly the tremors produced by changing the plates at the camera. I was much pleased with the working of the instrument, and believe that for portability, ease of installation, and steadiness of operation in all kinds of weather it is practical and efficient.

THE PHOTOGRAPHIC RESULTS.

My photographs were not very important because of using an uncorrected lens, so that it was not possible to obtain a clear sharp actinic focus. The run in 10 seconds was about 2 millimeters, and this amount of motion must be given to the telescope by the rotation of the driving rod. It was not possible to know before the eclipse the proper time exposures in order to obtain results from the corona with an enlargement of 36 diameters. The image on the plate was 8 centimeters, or 3¼ inches; the coronal rays extend to 1.5 centimeters, or six-tenths of an inch; that is, about one-third the solar radius. Several prominences were observed on various portions of the limb. The first and second plates were lost by an underexposure of 1 and 4 seconds, respectively; the exposure of 8 seconds brought down the inner corona in full, and that of 12 seconds began to blacken the inner portions. An exposure of 10 seconds was about right. Hence, where 2 seconds would be enough in the focus of a long lens, 10 seconds were required for this enlargement. It is perfectly practicable to obtain four plates of 10 seconds exposure during the first minute of the eclipse; the change to a second camera can be made in 15 seconds; thus, in an eclipse of average duration, at least eight long exposure plates ought to be made with such a telescope. I have been explicit in giving the details of the mounting, as it will save others who may wish to try this plan some preliminary investigations, and it is most important to have a clear idea of the main features of the work before beginning operations.

The aspect of the corona, as seen at Newberry, showed that it consisted of a bright inner ring of light-yellow color, and then spread out in pearly sheets finely striated with lines. The polar rays were distinctly detached from one another; the equatorial wings were irregularly widened in a fish-tail shape on the preceding side, and contracted in a conical shape on the following side. Further remarks on the corona are to be found in Chapter 4.

The preparations for observing the shadow bands consisting in laying down a long canvas oriented to the points of the compass, and in preparing two boards painted alternately in black and white foot spaces, by means of which the width of the bands might be estimated; also two sticks were at hand ready to lay down on the sheet parallel to the bands. Nothing was seen of the bands before totality began; as the totality was ending faint shadows an inch or two wide flitted over the sheet, and their direction was marked. Generally the phenomenon was disappointing, and the fact that it was inconspicuous is attributed to the remarkably quiet state of the atmosphere above the place. This subject will be discussed in Chapter 3.

GENERAL REMARK.

We may make one general remark regarding the relation of preliminary meteorological surveys to the selection of sites for eclipse stations. To simply determine the average conditions as to temperature, humidity, and relative cloudiness, on such a day as might be expected for the eclipse is really misleading, if the conclusion stops there. The temperature during the eclipse drops from 4° to 8° F., and this chill of the atmosphere is often enough to produce a cloud stratum in what would otherwise be a clear sky. If the humidity averages high enough to condense when the temperature falls a few degrees, the site is unfit for observations. This is often the case on the coast in tropical countries and on islands, so that these are likely to be unsuitable for purposes of observation. There are several instances of failure of eclipse expeditions due to this cause alone. It is better to seek an inland station at some considerable elevation, if possible, and then the task of transporting heavy instruments becomes a serious difficulty. An efficient light-weight apparatus is therefore a very great desideratum.

CHAPTER 2.

THE METEOROLOGICAL CHANGES CAUSED BY THE SHADOW OF THE MOON DURING THE ECLIPSE.

THE PREPARATION FOR THE SPECIAL METEOROLOGICAL OBSERVATIONS.

By direction of the Chief of the Weather Bureau a form was prepared for recording the meteorological observations required for determining the influence of the shadow of the moon in its passage through the earth's atmosphere. These records contain accurate readings of the barometer, the wet and dry bulb thermometers, the direction and velocity of the wind, and the amount of cloudiness. The method of observing is precisely that practiced by the observers of the United States Weather Bureau in their regular line of duty. The instruments were all standard and the corrections were properly applied, so that the resulting data are first class in every particular. Since the instruments and method of observing have been suitably described in the reports of the Weather Bureau and are already well known, it is not necessary to make any further preliminary remarks regarding the character of the observations themselves. The unusual advantage pertaining to this eclipse was the fact that it passed over a region so well supplied with meteorological instruments and observers that it was not considered important to make any further preparations than to provide suitable forms for recording the readings taken at certain specified times.

Thus we had such stations as New Orleans, Raleigh, Norfolk, Mobile, Charlotte, and Montgomery located directly in the path of totality, and better equipped than it would be possible to provide by any temporary installments in control of eclipse parties in the field. It also gave us an excellent opportunity to eliminate the specific effect of the shadow cone from the diurnal range by including a large number of stations located outside the path of the totality. There has always been much uncertainty in ascribing to the shadow its own proper effect, because it was not known how far the diurnal range on that occasion varied from the mean diurnal range in the several elements. In order to eliminate the shadow effect from the diurnal range it was decided to examine a wide belt on each side of the total-eclipse path, and accordingly all our stations within 500 miles of the central line were included in the programme. We have, therefore, reports from 62 stations, covering quite uniformly a belt 1,000 miles wide, through the midst of which the shadow passed, and the following data are compiled from this large group of reporting stations. Fortunately the weather was very propitious for such observations, since the atmospheric conditions were practically quiescent except on the extreme northern border of this wide belt, so that only very slight cyclonic conditions were superposed upon the diurnal variation. By taking the records extending from Texas to New England and from the Ohio Valley to the Gulf of Mexico it is certain that the mean variations on May 28, 1900, must have been practically free from any important cyclonic movements, so that any other variation caused by the shadow would be clearly defined as such and attributable only to that cause.

The observations were assigned to certain minutes in the following way: The time of maximum obscuration was computed for all the stations, including those within and those outside the shadow path; then an observation was assigned to that instant, others to the next 5 minutes later and earlier, and others at intervals of 15 minutes backward and forward, so that the entire number of separate observations was 25 for each station. The observers were requested to continue the observations hourly if convenient till night, but as only a few complied the record is restricted to those grouped uniformly about the central hour of maximum obscuration.

TABLES OF THE VARIATION OF THE METEOROLOGICAL CONDITIONS OF THE ATMOSPHERE.

The following tables, 3 to 9, have been compiled from the original records of the observations. They assume the value of the atmospheric element as observed at the moment of totality or greatest obscuration to be the *normal* value from which the variations are computed, and these are found for all the stations in Table 3, which gives the pressure, temperature, vapor tension, wind velocity and direction, and the observed cloudiness at that instant for each of the 62 stations.

Since the variation on itself must be zero at totality, this is entered as .000 under the thirteenth column of Table 4, and likewise in Tables 5, 6, and 7, and is also marked "total." The variations are reckoned backward and forward by subtracting this central value from those observed at the several minutes of the observations before and after totality. The times of totality are given in the last column of Table 3. The algebraic sum of the time there given, which is seventy-fifth meridian, and the intervals beginning -165^m in column 1 and ending $+150^m$ in column 24 of the several tables, gives the seventy-fifth meridian time at which the local observations were made. Since the important point to be secured by the observations is the relative effect of the passage of the moon's shadow through the earth's atmosphere, it is obvious that this arrangement of the data brings out the required result with a minimum of computation.

The stations are arranged in the order of their distance in miles from the center of the shadow path; they are marked N. for north and S. for south, to distinguish on which side of it they are located. The first group contains the 6 stations which are within or on the very edge of the shadow, and so must have received the full influence of the meteorological effect. It is properly these to which the computations for any physical variation on the elements should be applied, and yet the partial phase up to 500 miles from the center involved an obscuration of at least nine-tenths of the light of the sun, so that all these stations ought to be influenced almost as much as the central group. By extending the compilation to so many stations situated on the north and south, and along the line of the eclipse from east to west, the mean values of the groups tend to eliminate the local cyclonic conditions prevailing at that hour. Since the lapse of time between the first and the last minute of totality in the United States is only 53 minutes—that is, from 8.24 at Corpus Christi to 9.17 at Eastport, the range in the ordinary diurnal variation can be neglected, especially during the early forenoon hour when the progression is steady and not changed by any maximum or minimum occurring at that time. The stations are divided into groups, and the means are taken.

Then the 62 stations occurring in the 9 groups are collected in a general mean at the end, and by inspection one can scrutinize the variations of any group or of any single station from this average value. The mean time of all the stations for the instant of the average mean or central totality is $8^h\ 47^m\ 30^s$, seventy-fifth meridian time. In order to display the significance of these variations in the several groups and for the general mean, the data of Tables 4 to 8 inclusive have been transferred to Charts 7 to 11 respectively. These give the variations in the barometric pressure, the temperature, the vapor tension, the wind velocity, and the wind azimuth in succession. The following remarks therefore depend upon this exhibit of the meteorological data, and they are readily verified by the reader from an inspection of the charts.

THE BAROMETRIC PRESSURE.

The trend of all the barometric variation lines of Chart 7 is upward to higher pressures with the lapse of time. Since the mean time of totality is $8^h\ 47^m$, this increase is in conformity with the course of the diurnal range, as may be seen by consulting Chart 44, International Cloud Report, page 466, at the latitude 40° and for the hour 9 a. m. Since the eclipse extended to about 10.30 a. m., the falling off from the morning maximum is just about to set in, and this is shown by the drop in the curves from number 19, which is 1h 15m after the totality. An inspection of these curves for evidences of characteristic changes in the pressure due to the effect of the moon's shadow shows that there may be a slight rise at Nos. 15, 16, that is 15 to 30 minutes past totality, with drops at Nos. 10, 11 and Nos. 17, 18; but this is very uncertain, and the mean curve is so smooth that this can not be positively asserted. There can be a variation of only a very few thousandths of an inch when the average of any large number of good barometers is taken. From the action of the pressure at individual stations there might be drawn some other conclusions regarding these pressure changes, which would yet be quite erroneous as regards the same when all local modifications are eliminated by using many station records. It was evidently such individual local variations which must have been used by Mr. H. H. CLAYTON in forming his theory regarding the effect of the moon's shadow on the pressure of the atmosphere.*

TABLE 3.—*The meteorological data at the several stations for the moment of totality from which the variations were computed.*

Stations	Pressure	Temperature	Vapor tension	Wind	Clouds		Total	
							h.	m.
New Orleans	29.966	76.0	.783	3 SE.	1 S. Cu.	S.	8	31
Raleigh	29.712	71.1	.432	4 SW.	1 Ci.	W.	8	49
Norfolk	30.008	68.5	.448	5 S.	....	....	8	53
Mobile	30.005	72.8	.732	3 NE.	3 Cu.	E.	8	33
Charlotte	29.285	67.0	.402	8 SW.	1 Ci.	W.	8	46
Montgomery	29.844	72.0	.595	1 E.	1 S.	....	8	37
Means	**29.808**	**71.2**	**.565**	**4 S.**	**1**	**SW.**		
Atlanta	28.892	68.8	.432	8 SW.	1 A. S.	W.	8	40
Pensacola	30.000	74.0	.732	12 E.	3 Cu.	E.	8	33
Meridian	29.668	71.1	.684	3 S.	2 S. Cu.	SW.	8	35
Kitty Hawk	30.089	63.0	.448	1 S.	....	....	8	53
Hatteras	30.118	65.6	.448	2 SW.	....	....	8	51
Lynchburg	29.329	66.5	.481	2 SW.	1 Ci.	....	8	51
Wilmington	30.021	68.9	.417	6 W.	......	....	8	46
Galveston	29.918	77.2	.732	0	2 S. Cu.	SE.	8	27
Charleston	30.091	70.1	.432	7 W.	6 Ci.	NW.	8	44
Atlantic City	30.027	56.7	.417	6 S.	1 Ci. S.	N.	8	59
Corpus Christi	29.937	75.0	.732	4 S.	1 Cu.	S.	8	24
Chattanooga	29.317	64.3	.417	1 S.	1 S. Cu.	NW.	8	41
Vicksburg	29.770	71.6	.684	5 SE.	1 A. Cu.	SW.	8	34
Savannah	30.052	69.3	.481	5 W.	8 Ci. S.	W.	8	40
Knoxville	29.064	66.0	.481	6 S.	1 A. S.	SW.	8	44
Washington	29.933	63.8	.387	4 S.	10 S.	W.	8	55
Baltimore	29.921	68.0	.373	3 SW.	7 Ci. Cu.	W.	8	56
Nantucket	30.171	47.8	.310	19 NE.	10 S.	NE.	9	08
Philadelphia	29.957	64.8	.481	6 E.	7 A. Cu.	NW.	8	59
Block Island	30.156	50.3	.310	23 NE.	10 S.	NE.	9	05

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*The Eclipse Cyclone and the Diurnal Cyclones. H. Helm Clayton, Ann. Harv. Coll. Obsy., Vol. XLIII, Part 1, 1901.

Proceedings of the American Academy of Arts and Sciences, Vol. XXXVI, No. 16, January, 1901.

Discussion of these papers, Science, March 1, April 12, and May 10, 1901.

Table 3.—*The meteorological data at the several stations for the moment of totality from which the variations were completed*—Continued.

Stations	Pressure	Temperature.	Vapor tension.	Wind.	Clouds.		Total.	
							h.	*m.*
New York	29.791	55.8	.387	27 NE.	10 S.	NE.	9	02
New Haven	30.060	52.4	.298	14 NE.	10 S.	NE.	9	04
Jacksonville	30.062	73.1	.536	6 E.	1 A. Cu.	SW.	8	38
Harrisburg	29.663	65.0	.402	4 W.	8 A. Cu.	W.	8	58
San Antonio	29.256	70.0	.684	......	4 S. Cu.	SE.	8	26
Nashville	29.481	70.2	.536	3 E.	6 A. Cu.	SW.	8	42
Shreveport	29.744	71.8	.660	4 SW.	1 A.S.	S.	8	32
Boston	30.126	48.0	.246	10 N.	10 S.	NE.	9	08
Palestine	29.446	69.2	.638	6 S.	Clear		8	30
Parkersburg	29.389	64.0	.499	2 SE.	10 A. S.	SW.	8	51
Lexington	28.989	66.8	.536	7 S.	3 A. Cu.	W.	8	47
Memphis	29.628	72.2	.616	10 SW.	4 A. S.	SW.	8	38
Pittsburg	29.148	71.0	.448	5 NW.	1 Ci. Cu.	....	8	55
Little Rock	29.634	70.0	.638	3 S.	8 Ci. Cu.	SW.	8	36
Albany	30.057	56.6	.277	9 S.	10 S. Cu.	W.	9	05
Louisville	29.464	70.3	.555	4 S.	4 A. Cu.	W.	8	46
Binghamton	29.145	62.1	.432	6 NW.	4 A. S.	W.	9	01
Portland	30.170	48.0	.180	11 NE.	6 A. S.	NE.	9	10
Cincinnati	29.335	66.5	.555	8 N.	10 N.	NW.	8	48
Cairo	29.638	67.3	.638	4 SE.	4 A. S.	SW.	8	41
Tampa	30 029	74.0	.660	5 E.	10 A. Cu.	SW.	8	33
Columbus	29.154	65.8	.481	5 SW.	3 A. S.	W.	8	51
Eastport	30.193	47.0	.245	3 N.	1 S.	W.	9	17
Northfield	29.281	50.3	.334	5 S.	10 N.	S.	9	08
Cleveland	29.186	62.5	.448	5 NE.	10 S. Cu.	SW.	8	54
Erie	29.276	65.0	.465	6 SW.	10 S. Cu.	SW.	8	56
Oswego	29.711	56.2	.417	5 N.	2 A. S.	W.	9	02
Indianapolis	29.129	63.3	.517	14 S.	5 S. Cu.	W.	8	48
Rochester	29.507	63.0	.432	5 N.	1 Ci.	W.	9	00
Sandusky	29.317	62.0	.499	4 S.	10 A. S.	SW.	8	53
Buffalo	29.213	66.0	.448	6 E.	10 S. Cu.	SW.	8	59
Abilene	28.100	68.0	.555	9 SE.	4 Ci.	W.	8	29
St. Louis	29.370	74.0	.575	5 S.	3 A. Cu.	W.	8	42
Jupiter	30.025	76.2	.707	9 NE.	10 S.	NE.	8	34
Springfield	28.759	65.6	.595	6 S.	4 A. Cu.	SW.	8	39
Key West	29.993	75.8	.707	7 E.	2 A. S.	SE.	8	29
Means	**29.641**	**65.0**	**.502**					

TABLE 4.—*Pressure variations during the total eclipse of May 28, 1900.*

[Referred to the pressure at the moment of totality.]

Station	Dist. Cent.	1 -165	2 -150	3 -135	4 -120	5 -105	6 -90	7 -75	8 -60	9 -45	10 -30	11 -15	12 -5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
1. New Orleans	0	-.022	-.014	-.016	-.013	-.012	-.013	-.008	-.004	-.001	.000	+.001	+.001	.000	+.001	+.005	+.005	+.010	+.013	+.011	+.007	+.011	+.005	+.003	+.005
Raleigh	6 N	-49	-47	-36	-32	-30	-24	-21	-17	-14	-10	-7	-3	.000	+2	-5	-4	-5	-1	-1	-3	-7	-10	-10	-13
Norfolk	15 N	-27	-34	-24	-21	-20	-17	-12	-12	-10	-9	-7	-1	.000	-3	-1	-1	-2	+5	+5	+7	+7	+1	-3	+3
Mobile	25 S	-24	-26	-25	-23	-24	-22	-20	-15	-13	-2	0	0	.000	0	-6	-8	......	......	......	......	......	......	......	......
Charlotte	25 N	-34	-28	-28	-25	-19	-18	-11	-7	-5	-2	-1	0	.000	+4	+3	+4	+1	+6	+6	+5	+5	+6	+5	+3
Montgomery	27 N	14	-9	-6	-9	-5	3	-2	+2	+1	+3	+3	0	.000	+2	+8	+7	+6	+10	+12	+6	+5	+1	-3	+1
Means	**16**	**-28**	**-26**	**-23**	**-21**	**-18**	**-16**	**-12**	**-9**	**-7**	**-3**	**-2**	**-1**	**.000**	**+1**	**+1**	**+1**	**+2**	**+7**	**+7**	**+4**	**+4**	**+1**	**-2**	**0**
2. Atlanta	40 N	-26	-25	-25	-23	-20	-15	-11	-9	-8	-4	-5	0	.000	0	0	0	-4	-1	+2	+4	+2	0	0	-1
Meridian	95 N	-27	-20	-16	-11	-10	-7	-7	-5	-2	+2	5	+1	.000	+3	+2	+2	+1	-1	+2	+4	+3	+3	+4	0
Lynchburg	110 N	-19	-19	-18	-18	-10	-9	-9	+5	+6	+3	+1	+1	.000	0	0	+6	+6	+7	+7	+8	+7	-4	-9	-16
Galveston	125 N	-29	-29	-27	-27	-24	-22	-20	-19	-15	-3	-3	-2	.000	0	+12	+13	+2	+1	+1	+2	+2	+5	+7	+7
Atlantic City	135 N	-29	-19	-23	-25	-9	-12	-13	-9	+3	+1	+1	0	.000	+6	+12	+9	+19	+29	+30	+38	+41	+37	+39	+34
Corpus Christi	140 N	-35	-35	-35	-33	-29	-26	-21	-18	-14	-10	5	-1	.000	+1	+4	+8	+10	+14	+16	+16	+14	+13	+10	+9
Chattanooga	140 N	-32	-28	-22	-22	-17	-9	-6	-7	-5	-4	-2	-2	.000	-1	0	+1	+1	-1	-1	0	0	-1	-2	-3
Vicksburg	155 N	-32	-26	-27	-23	-20	-19	-17	-14	-15	-12	-7	-1	.000	0	0	+1	+2	+1	......	......	-5	-7	-9	......
Knoxville	160 N	-29	-28	-11	-11	-9	-8	-4	-4	-4	-3	-1	0	.000	+1	+1	+1	+1	+1	+5	+5	+2	-5	-5	7
Washington	160 N	-26	-24	-23	-19	-12	-7	0	+1	0	-2	+3	+4	.000	+7	+7	+13	+19	+26	+24	+24	+22	+20	+16	+12
Baltimore	180 N	-34	-29	-11	-18	-13	-9	-6	-5	-4	-3	-2	-1	.000	+1	+2	+3	+6	+8	+9	+9	+10	+10	+8	+8
Nantucket	180 N	-73	-57	-44	-40	-32	-32	-27	-24	-18	-9	-5	-4	.000	+3	+4	+7	+17	+23	+26	+27	+32	+32	+39	+47
Philadelphia	190 N	-40	-36	-32	-30	-31	-28	-24	-23	-20	-16	-7	-3	.000	+1	+6	+17	+24	+25	+29	+32	+33	+34	+36	+39
Means	**139**	**-33**	**-29**	**-24**	**-23**	**-18**	**-16**	**-13**	**-10**	**-7**	**-5**	**-3**	**-1**	**.000**	**+2**	**+4**	**+6**	**+8**	**+10**	**+13**	**+14**	**+13**	**+11**	**+10**	**+11**
3. Block Island	210 N	-58	-56	-48	-44	-31	-18	-13	-8	-8	-3	+1	-2	.000	0	+2	+9	+13	+16	+25	+28	+31	+39	+40	+42
New York	220 N	-42	-33	-20	-24	-23	-7	+5	+10	+5	+2	+1	0	.000	+6	+11	+14	+20	+39	+42	+42	+43	+44	+43	+54
New Haven	240 N	-57	-46	-42	-34	-22	-25	-18	-19	-18	-8	-3	0	.000	+1	+5	+7	+13	+16	+22	+23	+29	+32	+34	+42
Harrisburg	260 N	-24	-29	-27	-22	-21	-18	-11	-7	0	0	+8	+5	.000	+5	+3	+8	+12	+20	+20	+14	+20	+21	+22	+23
San Antonio	260 N	-46	-44	-42	-43	-36	-23	-26	-30	-30	-22	-20	-12	.000	+2	-11	-12	-10	-11	-9	-11	-11	-12	-12	-14
Nashville	260 N	-10	-9	-8	-5	-5	-3	-3	-1	-1	+1	+2	+1	.000	0	-1	-4	-5	-7	-6	+2	+6	+11	+14	+15
Shreveport	260 N	-25	-22	-19	-14	-12	-8	-11	-11	-11	-5	-4	-3	.000	+2	+4	+1	+4	+6	+13	+11	+4	+5	+1	+6
Boston	280 N	-63	-53	-51	-46	-47	-43	-27	-19	-14	-11	-5	-2	.000	-1	+2	-1	+4	+8	+16	+17	+24	+26	+28	+32
Means	**249**	**-41**	**-37**	**-32**	**-29**	**-25**	**-18**	**-13**	**-11**	**-10**	**-6**	**-3**	**-2**	**.000**	**+2**	**+2**	**+3**	**+6**	**+11**	**+15**	**+16**	**+18**	**+21**	**+21**	**+25**
4. Palestine	300 N	-16	-13	-20	-7	+2	-5	0	+3	+6	+6	+6	0	.000	+10	+16	+14	+16	+15	+19	+25	+26	+26	+23	+16
Parkersburg	300 N	-10	-7	-3	-2	0	+1	+3	+3	+4	+11	+16	+4	.000	+4	+5	+7	+9	+9	+11	+11	+12	+13	+14	+14
Lexington	300 N	-17	-14	-13	-15	-18	-14	-13	-11	-9	-3	-1	0	.000	+1	+2	+2	+2	+1	-4	0	+5	+3	+7	+4
Memphis	300 N	-37	-36	-35	-32	-30	-26	-25	-18	-16	-8	-7	0	.000	-2	-2	-8	+2	+3	+3	+4	+9	+9	+12	+7
Pittsburg	335 N	-29	-29	-18	-16	-18	-11	-16	-6	-5	-5	0	0	.000	+1	+6	+1	-2	+2	+2	+5	+2	-5	-8	-10
Little Rock	340 N	-23	-23	-18	-18	-16	-16	-20	-10	-10	-6	-6	0	.000	0	+4	+4	+9	+5	+5	+10	+15	+15	+20	+20
Albany	345 N	-49	-44	-24	-23	-11	-10	-11	-10	-5	-6	-4	-1	.000	-1	-1	+7	+14	+14	+28	+31	+32	+34	+49	+50
Louisville	350 N	-9	-8	-8	-12	-14	-15	-9	-10	-9	-4	-3	-3	.000	-1	-3	-2	-5	-6	-7	-9	-9	-10	-6	-7

TABLE 4.—*Pressure variations during the total eclipse of May 28, 1900*—Continued.

Station.	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +130
4. Binghamton	350 N	− 13	− 13	− 2	+ 20	+ 24	+ 24	+ 25	+ 23	+ 16	+ 11	+ 3	− 5	.000	+ 1	− 1	− 1	+ 10	+ 12	+ 13	+ 8	+ 1	− 1	+ 7	− 1
Portland	360 N	− 65	− 62	− 54	− 45	− 36	− 38	− 35	− 21	− 22	− 13	− 3	− 4	.000	+ 3	+ 7	+ 11	+ 16	+ 18	+ 15	+ 14	+ 4	+ 4	+ 1	+ 5
Cincinnati	370 N	− 8	+ 2	− 8	− 18	− 11	− 2	+ 5	+ 13	+ 13	+ 13	+ 8	0	.000	+ 3	+ 7	+ 10	+ 20	+ 30	+ 34	+ 29	+ 19	+ 29	+ 19	+ 39
Cairo	380 N	− 17	− 10	− 2	− 5	− 10	− 9	− 10	− 7	− 8	− 5	− 4	0	.000	+ 1	+ 1	0	− 1	+ 1	+ 4	+ 6	+ 10	+ 9	+ 7	+ 4
Columbus	380 N	− 23	− 22	− 17	− 8	+ 3	− 2	− 2	− 2	− 2	+ 1	+ 1	0	.000	0	+ 1	+ 4	+ 5	+ 4	+ 7	+ 12	+ 18	+ 19	+ 23	+ 27
Eastport	390 N	− 7	− 7	− 6	− 3	− 2	− 1	+ 2	+ 4	+ 4	+ 2	+ 3	+ 2	.000	− 1	− 1	− 1	− 1	− 1	0	0	+ 1	+ 1	0	− 2
Means	**343**	**− 23**	**− 20**	**− 16**	**− 13**	**− 10**	**− 9**	**− 8**	**− 4**	**3**	**0**	**0**	**0**	**.000**	**+ 1**	**+ 2**	**+ 3**	**+ 7**	**+ 8**	**+ 9**	**+ 10**	**+ 10**	**+ 10**	**+ 12**	**+ 12**
5. Northfield	425 N	− 51	− 43	− 41	− 34	− 29	− 22	− 18	− 18	− 16	− 11	− 5	− 2	.000	+ 1	+ 6	+ 11	+ 19	+ 21	+ 27	+ 28	+ 34	+ 42	+ 48	+ 42
Cleveland	445 N	+ 11	+ 14	+ 14	+ 14	+ 12	+ 17	+ 16	+ 14	+ 15	+ 12	+ 5	+ 5	.000	− 1	+ 1	+ 3	+ 16	+ 9	+ 10	+ 14	+ 25	+ 30	+ 36	+ 42
Erie	450 N	− 42	− 40	− 39	− 38	− 34	− 32	− 23	− 7	− 3	+ 3	+ 3	0	.000	− 1	− 2	0	+ 4	+ 13	+ 19	+ 24	+ 24	+ 15	+ 4	+ 3
Oswego	450 N	− 23	− 22	− 21	− 21	− 19	− 17	− 14	− 12	8	− 3	− 2	0	.000	0	+ 7	+ 10	+ 16	+ 21	+ 21	+ 21	+ 21	+ 23	+ 27	+ 28
Indianapolis	450 N	− 10	+ 4	− 17	− 18	+ 24	+ 13	0	− 1	− 8	− 4	− 3	+ 4	.000	− 6	0	− 7	− 14	+ 23	+ 27	+ 25	+ 27	+ 24	+ 27	+ 27
Rochester	460 N	− 40	− 36	− 38	− 32	− 32	− 28	− 22	− 12	− 9	− 6	5	− 5	.000	0	0	+ 3	+ 3	+ 3	+ 11	+ 18	+ 9	+ 8	+ 8	+ 13
Sandusky	465 N	0	− 2	− 1	− 2	− 1	− 2	− 11	12	16	− 21	− 17	− 12	.000	+ 6	+ 9	+ 27	+ 31	+ 33	+ 35	+ 38	+ 39	+ 41	+ 43	+ 43
Buffalo	465 N	− 19	− 23	− 20	− 10	− 10	− 11	− 14	− 4	+ 4	0	+ 1	− 1	.000	0	+ 1	+ 8	+ 16	+ 18	+ 22	+ 24	+ 30	+ 31	+ 32	+ 33
Abilene	470 N	− 5	− 13	− 13	− 15	− 15	− 15	− 18	− 13	− 8	− 8	− 4	0	.000	0	− 1	+ 1	+ 5	+ 23	+ 22	+ 22	+ 16	+ 19	+ 19	+ 18
St. Louis	500 N	13	− 10	− 9	− 10	− 8	− 7	− 7	− 9	− 10	− 10	− 5	− 2	.000	0	− 2	0	− 2	0	+ 2	− 1	0	− 2	− 1	− 1
Springfield, Mo.	520 N	− 23	− 21	− 21	− 24	− 25	− 24	− 21	− 19	− 11	− 7	− 4	6	.000	+ 2	− 1	0	+ 3	+ 4	+ 5	+ 9	+ 10	+ 11	+ 11	+ 10
Means	**464**	**− 20**	**− 17**	**− 19**	**− 17**	**− 12**	**− 12**	**− 12**	**− 8**	**− 6**	**− 5**	**− 3**	**− 2**	**.000**	**0**	**+ 2**	**+ 5**	**+ 9**	**+ 15**	**+ 18**	**+ 20**	**+ 21**	**+ 22**	**+ 23**	**+ 23**
6. Pensacola	65 S	− 34	− 32	− 24	− 22	− 21	− 20	− 10	− 6	− 5	− 2	− 4	− 1	.000	+ 1	+ 1	+ 7	+ 9	+ 10	+ 10	+ 11	+ 13	+ 15	+ 14	+ 12
Kitty Hawk	100 S	− 52	− 42	− 45	− 40	− 37	− 17	− 14	− 15	− 15	− 15	− 10	− 10	.000	+ 10	+ 3	+ 3	− 10	− 10	0	+ 10	+ 4	+ 7	+ 7	+ 7
Hatteras	100 S	− 51	− 44	− 41	− 36	− 27	− 20	− 16	− 17	− 18	− 11	− 11	− 1	.000	0	+ 12	+ 12	+ 12	+ 12	+ 16	+ 19	+ 17	+ 17	+ 17	+ 20
Means	**88**	**− 46**	**− 39**	**− 37**	**− 33**	**− 28**	**− 19**	**− 13**	**− 13**	**− 13**	**− 9**	**− 8**	**− 4**	**.000**	**+ 4**	**+ 5**	**+ 7**	**+ 4**	**+ 4**	**+ 9**	**+ 13**	**+ 11**	**+ 13**	**+ 13**	**+ 13**
7. Wilmington	110 S	− 26	− 27	− 24	− 23	− 20	− 13	− 9	− 11	− 7	− 4	− 1	− 1	.000	+ 5	+ 6	+ 8	+ 10	+ 10	+ 13	+ 14	+ 15	+ 14	+ 12	+ 9
Charleston	125 S	− 33	− 33	− 25	− 24	− 24	− 16	− 3	− 5	− 5	− 3	− 3	− 1	.000	+ 2	+ 10	+ 10	+ 12	+ 17	+ 17	+ 23	+ 20	+ 17	+ 14	+ 13
Savannah	158 S	− 27	− 21	− 20	− 22	− 20	− 16	− 10	− 9	− 5	0	− 2	0	.000	+ 1	+ 4	+ 7	+ 13	+ 14	+ 17	+ 17	+ 22	+ 24	+ 25	+ 25
Means	**131**	**− 29**	**− 27**	**− 23**	**− 23**	**− 21**	**− 15**	**− 7**	**− 8**	**− 6**	**− 2**	**− 2**	**− 1**	**.000**	**+ 3**	**+ 7**	**+ 8**	**+ 12**	**+ 14**	**+ 16**	**+ 18**	**+ 19**	**+ 18**	**+ 17**	**+ 16**
8. Jacksonville	240 S	− 33	− 32	− 31	− 25	− 22	− 18	− 9	− 4	− 4	− 6	− 3	0	.000	+ 3	+ 3	+ 3	+ 5	+ 10	+ 13	+ 17	+ 16	+ 17	+ 13	+ 11
Tampa	380 S	− 26	− 26	− 25	− 25	− 20	− 14	− 8	− 4	− 6	− 6	− 2	0	.000	+ 4	+ 8	+ 8	+ 9	+ 9	+ 4	+ 6	+ 3	+ 3	+ 1	− 1
Means	**310**	**− 30**	**− 29**	**− 28**	**− 25**	**− 21**	**− 16**	**− 8**	**− 4**	**− 5**	**− 6**	**− 2**	**0**	**.000**	**+ 4**	**+ 6**	**+ 6**	**+ 7**	**+ 10**	**+ 8**	**+ 12**	**+ 10**	**+ 10**	**+ 7**	**+ 5**
9. Jupiter	500 S	− 34	− 32	− 28	− 25	− 23	− 19	− 17	− 18	− 13	− 7	− 6	− 4	.000	+ 1	+ 2	+ 2	+ 6	+ 7	+ 5	+ 3	+ 10	+ 12	+ 13	+ 13
Key West	600 S	− 36	− 30	− 32	− 33	− 29	− 27	− 33	− 25	− 24	− 8	− 5	− 5	.000	4	4	− 2	+ 3	+ 4	+ 6	+ 4	+ 2	+ 4	+ 6	+ 8
Means	**550**	**− 35**	**− 31**	**− 30**	**− 29**	**− 26**	**− 23**	**− 25**	**− 22**	**− 18**	**− 8**	**− 6**	**− 4**	**.000**	**− 2**	**− 1**	**0**	**+ 4**	**+ 6**	**+ 6**	**+ 4**	**+ 6**	**+ 8**	**+ 10**	**+ 10**
Means	....	− 29	− 26	− 23	− 21	− 17	− 14	− 11	− 8	− 7	− 4	− 2	− 1	.000	+ 1	+ 3	+ 4	+ 7	+ 10	+ 12	+ 13	+ 13	+ 13	+ 14	+ 14
Shadow variations	....	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	.001	−.003	−.005	−.006	−.002	.000	.000	.000	.000	.000	.000

CHART 7.

Barometric pressure variations.

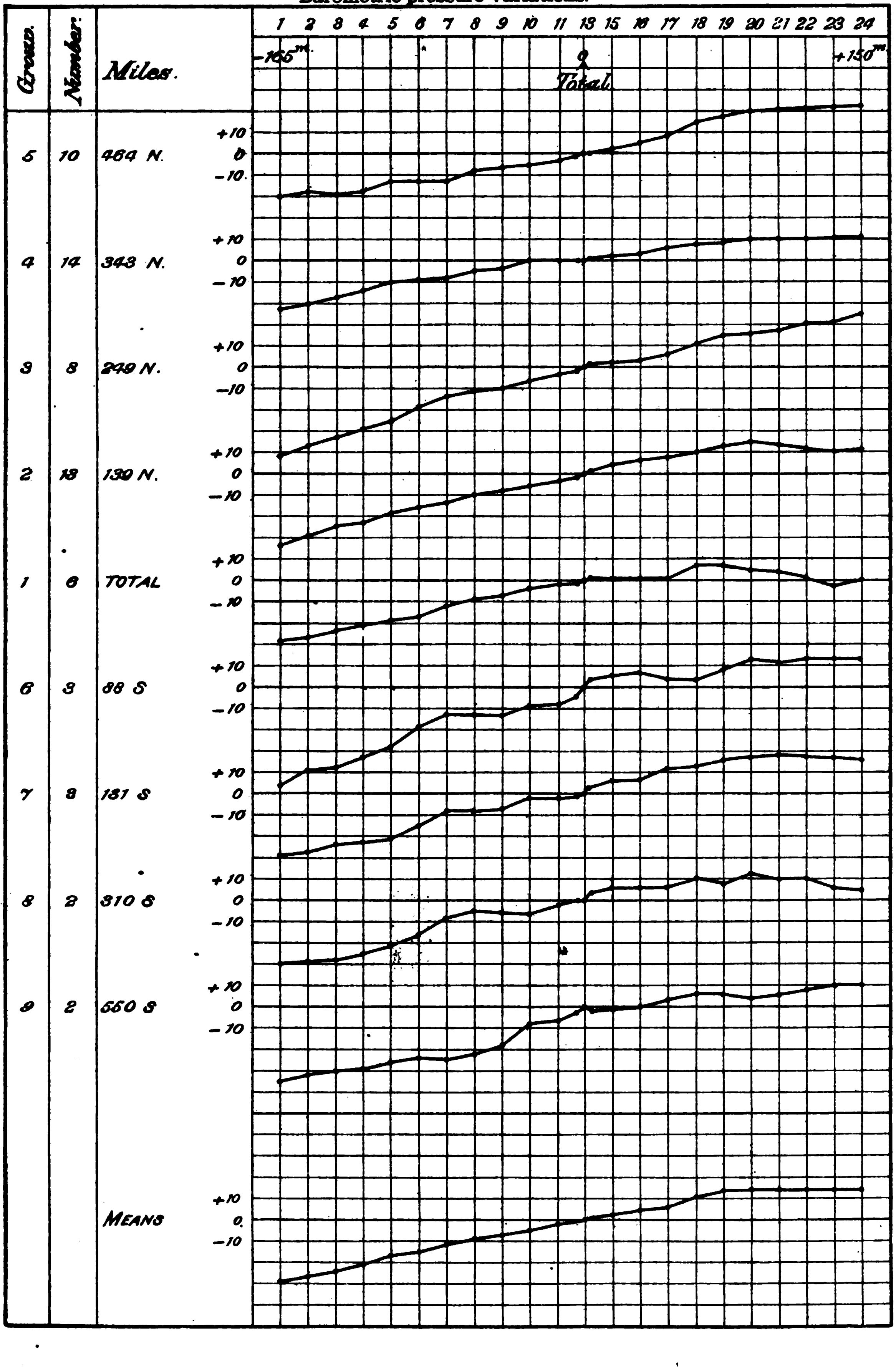


TABLE 5.—*Temperature variations during the total eclipse of May 28, 1900.*

[Referred to the temperature at the moment of totality.]

Station.	Dist. Cent.	1 -165	2 -150	3 -135	4 -120	5 -105	6 -90	7 -75	8 -60	9 -45	10 -30	11 -15	12 -5	13 Total.	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
1. New Orleans	0	- 0.6	- 0.8	- 1.0	- 1.0	- 0.9	- 0.4	+ 1.0	+ 1.5	+ 0.5	+ 0.5	+ 0.5	0.0	0.0	0.0	0.0	+ 0.6	+ 2.0	+ 2.0	+ 4.0	+ 5.0	+ 6.3	+ 6.3	+ 6.3	+ 5.1
Raleigh	6 N	- 6.7	- 5.8	- 4.9	- 4.3	- 5.1	- 4.9	- 3.1	- 1.7	- 0.6	- 0.5	- 0.3	- 0.8	0.0	- 1.4	- 1.7	- 1.6	- 0.1	+ 1.4	+ 3.4	+ 5.9	+ 8.4	+ 8.9	+ 9.9	+10.8
Norfolk	15 N	- 8.8	- 9.0	- 7.5	- 6.3	- 5.7	- 4.0	- 2.4	- 1.5	- 0.2	+ 0.9	+ 0.5	+ 0.1	0.0	- 0.3	0.5	- 1.0	- 0.3	+ 1.5	+ 4.3	+ 6.0	+ 6.5	+ 6.7	+ 8.0	+ 9.0
Mobile	25 S	- 2.0	- 2.0	- 2.3	- 1.8	- 1.8	- 1.8	- 1.3	+ 0.2	+ 1.2	+ 0.7	0.0	+ 0.2	0.0	0.0	+ 0.2	+ 0.2	+ 0.2	+ 1.2	+ 3.2	+ 5.2	+ 4.2	+ 6.2	+ 6.2	+ 8.2
Charlotte	25 N	- 7.2	- 6.5	- 5.0	- 5.0	- 3.0	- 2.0	- 0.8	+ 0.3	+ 1.3	+ 1.5	+ 1.0	+ 0.5	0.0	0.0	0.0	+ 0.8	+ 1.5	+ 3.5	+ 4.9	+ 6.0	+ 7.0	+ 7.0	+ 8.5	+10.0
Montgomery	27 N	- 4.5	- 4.4	- 3.7	- 2.4	- 1.9	- 1.0	+ 1.1	+ 1.0	+ 1.0	+ 2.0	+ 2.5	0.0	0.0	0.0	0.0	+ 1.5	+ 2.0	+ 3.5	+ 5.5	+ 5.5	+ 7.5	+ 8.5	+ 8.5	+ 9.0
Means	**16**	**- 5.0**	**- 4.8**	**- 4.1**	**- 3.5**	**3.1**	**- 2.4**	**- 0.9**	**0.0**	**+ 0.5**	**+ 0.9**	**+ 0.7**	**0.0**	**0.0**	**- 0.3**	**- 0.3**	**+ 0.1**	**+ 0.9**	**+ 2.2**	**+ 4.2**	**+ 5.6**	**+ 6.7**	**+ 7.3**	**+ 7.9**	**+ 8.7**
2. Atlanta	40 N	- 4.3	- 4.0	- 3.7	- 3.2	- 2.2	- 1.4	- 0.2	+ 1.1	+ 1.2	+ 1.0	+ 0.4	0.0	0.0	- 0.5	- 0.8	+ 0.2	+ 0.8	+ 2.2	+ 3.0	+ 4.4	+ 6.1	+ 6.4	+ 6.7	+ 6.7
Meridian	95 N	- 2.8	- 3.9	- 3.0	- 2.7	1.8	- 1.7	- 1.7	- 0.1	+ 0.4	+ 0.9	+ 0.6	+ 0.2	0.0	- 0.1	- 0.2	+ 0.6	+ 2.0	+ 3.9	+ 3.3	+ 4.9	+ 5.9	+ 7.0	+ 7.4	+ 8.3
Lynchburg	110 N	- 9.5	- 9.0	- 7.3	- 5.5	- 5.0	- 3.0	- 1.5	+ 1.3	+ 2.3	+ 2.2	+ 2.5	+ 0.5	0.0	- 0.5	0.0	+ 0.9	+ 2.6	+ 3.5	+ 5.5	+10.0	+10.0	+10.5	+14.5	+14.0
Galveston	125 N	- 1.4	- 1.3	- 1.3	- 1.2	- 1.0	- 1.0	- 0.7	+ 0.6	+ 2.0	+ 1.9	+ 0.8	+ 0.2	0.0	0.0	+ 0.2	+ 0.7	+ 2.3	+ 2.5	+ 2.0	+ 2.1	+ 3.9	+ 3.3	+ 1.9	+ 3.6
Atlantic City	135 N	+ 1.9	+ 2.0	+ 1.1	+ 1.3	+ 1.5	+ 1.3	+ 1.7	+ 1.6	+ 1.6	+ 0.3	+ 0.6	+ 0.3	0.0	- 0.2	0.0	+ 0.6	+ 1.8	+ 2.3	+ 3.5	+ 3.3	+ 2.8	+ 3.5	+ 3.3	+ 4.3
Corpus Christi	140 N	- 1.0	- 1.0	- 1.0	- 1.0	- 1.5	- 2.0	- 1.0	0.0	+ 1.0	+ 0.8	+ 1.0	0.0	0.0	0.0	0.0	+ 0.5	+ 2.0	+ 3.0	+ 4.2	+ 4.0	+ 4.6	+ 4.1	+ 4.2	+ 4.5
Chattanooga	140 N	- 6.3	- 6.3	- 6.1	- 5.3	- 4.9	- 4.3	3.2	- 2.3	0.3	+ 1.4	+ 1.7	+ 0.4	0.0	- 0.1	+ 0.4	+ 0.4	+ 1.7	+ 5.7	+ 5.9	+ 7.9	+ 9.5	+ 9.3	+11.2	+11.8
Vicksburg	155 N	- 1.5	- 1.5	- 1.6	- 2.0	- 1.8	- 1.3	- 0.6	+ 0.3	+ 0.6	+ 0.7	+ 0.4	+ 0.2	0.0	0.0	0.0	+ 0.5	+ 1.6	+ 2.7	+ 3.7	+ 4.6	+ 5.6	+ 6.0	+ 6.4	+ 7.1
Knoxville	160 N	- 6.9	- 7.0	- 5.7	- 4.7	- 3.8	- 2.6	- 1.7	- 0.5	+ 0.4	+ 0.5	+ 0.3	0.0	0.0	0.0	- 0.4	+ 1.3	+ 2.0	+ 2.8	+ 4.5	+ 7.0	+ 8.8	+10.8	+11.2	+12.0
Washington	160 N	- 1.8	- 1.5	- 0.8	- 0.3	+ 1.2	+ 0.7	+ 0.4	+ 0.7	+ 0.4	+ 1.0	+ 0.4	+ 0.2	0.0	+ 0.2	+ 0.2	+ 0.7	+ 2.2	+ 2.5	+ 3.7	+ 4.2	+ 4.4	+ 5.2	+ 5.6	+ 6.2
Baltimore	180 N	- 3.0	- 3.0	- 3.2	- 3.9	- 2.0	- 3.0	- 1.0	- 1.0	- 0.9	- 0.4	0.0	0.0	0.0	0.0	+ 0.5	+ 0.5	+ 0.5	+ 1.0	+ 2.5	+ 3.5	+ 4.3	+ 4.0	+ 5.0	+ 7.0
Nantucket	180 N	+ 1.5	+ 1.5	+ 1.3	+ 1.3	+ 1.2	+ 1.2	+ 1.1	+ 0.2	+ 0.4	0.0	0.0	+ 0.2	0.0	- 0.3	+ 0.1	+ 0.4	+ 0.7	+ 0.2	+ 0.2	+ 0.2	+ 1.0	+ 1.4	+ 0.7	+ 1.0
Philadelphia	190 N	- 4.1	- 3.8	- 2.5	- 0.7	- 0.3	+ 2.5	+ 3.0	+ 3.3	+ 4.0	+ 3.2	+ 1.2	+ 0.2	0.0	- 0.8	- 0.8	- 0.8	- 0.2	- 0.4	- 0.1	+ 1.0	+ 1.7	+ 3.6	+ 2.9	+ 2.3
Means	**139**	**- 3.0**	**- 3.0**	**- 2.6**	**- 2.1**	**- 1.6**	**- 1.1**	**- 0.4**	**+ 0.4**	**+ 1.0**	**+ 1.0**	**+ 0.8**	**+ 0.2**	**0.0**	**- 0.2**	**- 0.1**	**+ 0.5**	**+ 1.5**	**+ 2.5**	**+ 3.2**	**+ 4.4**	**+ 5.3**	**+ 5.8**	**+ 6.2**	**+ 6.8**
3. Block Island	210 N	+ 0.7	- 0.3	- 0.3	- 0.5	- 0.3	- 0.3	+ 0.7	+ 0.7	+ 0.5	+ 0.7	+ 0.2	- 0.1	0.0	0.0	+ 0.3	+ 0.7	+ 0.9	+ 1.3	+ 1.7	+ 1.7	+ 1.7	+ 2.7	+ 1.9	+ 1.8
New York	220 N	+ 3.2	+ 2.7	+ 3.0	+ 2.0	+ 2.2	+ 1.5	+ 1.5	+ 0.7	+ 0.4	+ 0.7	+ 0.5	+ 0.2	0.0	+ 0.3	+ 0.7	+ 1.2	+ 1.5	+ 1.7	+ 2.2	+ 2.7	+ 3.7	+ 4.6	+ 4.7	+ 3.7
New Haven	240 N	+ 1.8	+ 2.6	+ 2.9	+ 3.6	+ 3.8	+ 4.4	+ 3.7	+ 3.8	+ 3.9	+ 2.6	+ 0.4	+ 0.3	0.0	- 0.2	0.0	+ 0.3	+ 0.8	+ 0.8	+ 0.7	+ 1.6	+ 2.4	+ 2.3	+ 2.5	+ 1.6
Harrisburg	260 N	- 3.0	- 2.8	- 3.0	- 1.5	- 0.7	- 1.9	- 1.5	- 0.2	- 1.0	- 1.0	- 0.5	0.0	0.0	0.0	0.0	0.0	+ 0.5	+ 2.0	+ 3.0	+ 4.0	+ 6.5	+ 6.0	+ 7.0	+ 7.6
San Antonio	260 N	- 2.0	- 2.0	- 2.0	- 2.0	- 1.8	- 1.5	- 0.6	- 0.6	+ 0.2	+ 0.8	+ 1.2	+ 0.5	0.0	0.0	+ 0.5	+ 1.0	+ 2.5	+ 2.0	+ 3.1	+ 4.0	+ 4.0	+ 5.0	+ 4.0	+ 5.3
Nashville	260 N	- 7.2	- 6.8	- 5.4	- 5.2	- 4.4	- 4.2	- 3.8	- 2.7	- 1.7	- 0.7	- 0.5	- 0.2	0.0	+ 0.4	+ 1.0	+ 1.8	+ 2.0	+ 6.3	+ 6.8	+ 7.3	+ 9.0	+ 6.8	+ 8.2	+ 7.4
Shreveport	260 N	- 3.9	- 3.9	- 3.8	- 3.6	- 3.5	- 3.6	- 1.8	- 0.8	- 0.1	+ 0.6	+ 0.3	+ 0.1	0.0	- 0.4	+ 0.3	+ 0.6	+ 2.7	+ 4.2	+ 4.2	+ 5.2	+ 6.5	+ 6.6	+ 7.9	+ 6.9
Boston	280 N	- 0.2	+ 0.3	0.0	+ 0.3	+ 1.0	+ 0.2	+ 0.8	+ 0.4	0.0	0.0	+ 0.9	0.0	0.0	0.0	0.0	0.0	- 1.0	- 0.5	- 0.6	- 1.0	- 1.0	- 0.5	- 0.7	- 0.4
Means	**249**	**- 1.3**	**- 1.3**	**- 1.1**	**- 0.9**	**- 0.5**	**- 0.7**	**- 0.1**	**+ 0.2**	**+ 0.3**	**+ 0.5**	**+ 0.3**	**+ 0.1**	**0.0**	**0.0**	**+ 0.4**	**+ 0.7**	**+ 1.2**	**+ 2.2**	**+ 2.6**	**+ 3.2**	**+ 4.1**	**+ 4.2**	**+ 4.5**	**+ 4.2**
4. Palestine	300 N	- 1.0	- 1.2	- 2.2	- 1.8	- 1.2	- 1.2	- 0.6	+ 0.8	+ 0.8	+ 0.9	+ 0.8	+ 0.2	0.0	- 0.2	- 0.2	- 0.6	- 0.1	+ 0.7	+ 1.8	+ 3.5	+ 4.1	+ 5.0	+ 5.2	+ 5.8
Parkersburg	300 N	- 2.7	- 2.0	- 2.0	- 1.5	- 1.2	- 1.2	- 1.0	- 1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+ 0.4	+ 0.5	+ 0.8	+ 3.0	+ 5.0	+ 6.0	+ 7.0	+ 9.0	+ 9.0
Lexington	300 N	- 5.8	- 5.6	- 5.5	- 5.2	- 4.2	- 3.5	- 2.3	- 2.0	- 0.8	+ 0.8	+ 1.0	+ 0.2	0.0	0.0	0.0	+ 0.9	+ 1.2	+ 3.6	+ 6.4	+ 7.4	+10.0	+ 8.7	+ 9.2	+ 8.8
Memphis	300 N	- 1.2	- 1.0	- 1.2	- 1.3	- 1.2	- 1.2	- 0.9	- 0.4	- 0.2	- 0.2	- 0.2	0.0	0.0	0.0	0.0	+ 0.8	+ 0.3	- 0.2	0.0	+ 0.3	+ 0.8	+ 0.6	+ 1.0	- 0.2
Pittsburg	335 N	- 6.0	- 4.0	- 6.0	- 5.0	- 4.0	- 2.0	- 2.0	- 1.0	0.0	+ 1.0	- 1.0	+ 1.0	0.0	- 0.5	- 1.0	- 1.0	0.0	0.0	+ 1.0	+ 1.5	+ 1.5	+ 3.0	+ 2.5	+ 2.0
Little Rock	340 N	- 4.0	- 3.5	- 4.0	- 4.0	- 3.0	- 2.0	- 1.0	- 0.5	+ 2.0	+ 2.0	+ 1.0	0.0	0.0	- 0.2	0.0	+ 0.8	+ 1.5	+ 2.0	+ 2.5	+ 2.7	+ 2.5	+ 2.5	+ 3.2	+ 3.0
Albany	345 N	+ 2.7	+ 0.9	+ 0.9	+ 1.2	+ 0.4	+ 0.9	+ 0.6	+ 0.6	+ 0.6	+ 0.6	- 0.1	- 0.2	0.0	- 0.2	- 0.3	- 0.1	- 0.4	+ 0.3	+ 0.6	+ 1.5	+ 1.5	+ 3.4	+ 2.2	+ 1.8
Louisville	350 N	- 6.5	- 6.4	- 6.3	- 5.3	- 5.0	- 3.4	- 1.4	- 0.4	+ 0.6	+ 1.2	+ 1.2	+ 0.7	0.0	- 0.1	- 0.3	+ 0.4	+ 1.7	+ 2.7	+ 4.7	+ 4.5	+ 6.3	+ 6.3	+ 6.3	+ 6.7

TABLE 5.—*Temperature variations during the total eclipse of May 28, 1900*—Continued.

Station.	Dist. Cent.	1 -165	2 -150	3 -135	4 -120	5 -105	6 -90	7 -75	8 -60	9 -45	10 -30	11 -15	12 -5	13 Total.	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
4. Binghamton	350 N	-1.9	-1.1	-1.6	-1.3	-1.1	-1.1	-1.5	-0.4	+0.9	+0.3	+0.3	+0.2	0.0	-0.1	+0.5	+0.5	+1.9	+2.9	+4.7	+6.9	+7.6	+7.4	+8.2	+11.4
Portland	360 N	+1.0	+1.0	+1.0	+1.0	+1.0	+1.2	+0.5	+0.7	+0.8	+1.0	+1.0	+0.5	0.0	0.0	0.0	+0.5	+0.5	+2.2	+4.0	+4.0	+3.0	+4.0	+3.5	+3.0
Cincinnati	370 N	-1.5	-1.5	-2.0	-2.5	-1.8	-1.5	-1.0	-0.7	-0.5	+0.5	+0.5	0.0	0.0	-0.5	+0.4	+0.3	+0.5	+0.5	+0.5	+0.5	+1.5	+1.5	+0.5	0.0
Cairo	380 N	0.0	-0.1	-1.3	-2.0	-1.2	+0.5	+0.4	+0.4	+0.8	+0.7	+0.6	+0.1	0.0	+0.1	+0.4	+0.5	+1.0	+1.4	+2.7	+3.2	+4.6	+5.4	+5.9	+7.6
Columbus	380 N	-5.3	-5.4	-4.7	-3.5	-2.2	-0.6	-0.6	-0.8	-0.4	+0.1	+0.2	+0.1	0.0	+0.3	+0.2	+0.5	+1.0	+3.3	+3.3	+2.4	+2.7	+3.1	+3.1	+3.2
Eastport	390 N	-5.0	-4.0	-3.0	-1.5	-1.0	0.0	+0.5	+0.5	+1.0	+1.0	+1.0	+0.5	0.0	0.0	+0.5	+1.0	+1.0	+2.0	+3.5	+2.5	+2.0	+3.0	+3.5	+5.0
Means	**343**	**-2.7**	**-2.4**	**-2.7**	**-2.3**	**-1.8**	**-1.1**	**-0.7**	**-0.3**	**+0.4**	**+0.7**	**+0.5**	**+0.2**	**0.0**	**-0.1**	**0.0**	**+0.4**	**+0.8**	**+1.6**	**+2.8**	**+3.8**	**+3.9**	**+4.4**	**+4.5**	**+4.0**
5. Northfield	425 N	+3.2	+3.2	+3.7	+3.5	+3.0	+2.7	+2.7	+3.7	+2.2	+1.5	+0.2	-0.1	0.0	0.0	-0.1	-0.3	0.0	0.0	-0.3	-0.5	-0.8	-1.3	-1.3	-0.5
Cleveland	445 N	-2.7	-2.2	-2.2	-2.2	-1.7	-1.8	-1.2	-0.9	-0.5	-0.3	+0.3	+0.3	0.0	-0.4	-0.4	-1.5	-2.3	-1.6	-0.8	-0.1	-0.1	+0.4	+0.6	+0.8
Erie	450 N	-2.7	-2.4	-2.2	-2.1	-2.0	-1.7	-1.0	-0.4	+0.3	+0.4	+0.4	+0.1	0.0	-0.1	-0.4	-0.5	-0.5	-0.2	-0.4	-0.8	-1.0	0.0	-0.1	+0.4
Oswego	450 N	+1.9	+2.6	+3.6	+2.7	+2.5	+3.7	+4.3	+4.4	+4.1	+4.4	+2.7	+2.0	0.0	+0.2	+0.9	+2.6	+1.7	+2.2	+3.5	+6.0	+6.1	+4.0	+4.3	+5.0
Indianapolis	450 N	-0.5	+0.7	+0.7	-0.1	-1.7	-1.3	-1.1	-0.3	+0.5	+1.0	+0.7	-0.5	0.0	-0.5	-0.2	-0.1	+1.4	-0.3	-0.3	-0.3	-1.3	-0.2	+0.1	+0.7
Rochester	460 N	-0.8	+1.0	+2.2	+3.0	+4.0	+4.7	+5.3	+3.3	+0.9	+2.0	+1.1	0.0	0.0	-0.2	-0.3	-2.0	-1.5	-0.5	+1.6	+1.4	+6.4	+5.3	+5.7	+6.4
Sandusky	465 N	-2.0	-1.5	-1.7	-1.9	-1.8	-1.4	-1.2	-0.2	+0.1	+0.3	+0.3	0.0	0.0	0.0	-0.5	-0.4	+0.6	+1.0	+0.4	+0.4	+0.5	+1.0	+1.2	+1.1
Buffalo	465 N	-4.2	-4.5	-4.2	-4.0	-2.7	-1.5	-0.5	-0.2	0.0	0.0	+0.2	+0.1	0.0	+0.2	+0.3	+1.0	+2.1	+0.8	+1.8	+2.0	+2.8	+1.9	+3.2	+5.1
Abilene	470 N	-3.2	-2.4	-2.0	-1.8	-1.0	-0.5	0.0	+0.2	+0.7	+0.9	+1.0	+0.4	0.0	0.0	+0.1	+0.1	+1.0	+2.5	+3.8	+6.0	+6.0	+7.0	+7.2	+7.5
St. Louis	500 N	-3.0	-3.1	-3.0	-2.0	-1.5	-1.0	-0.8	+0.2	+0.6	+1.0	+0.5	0.0	0.0	-0.4	-0.2	-0.1	+0.5	+1.0	+1.0	+2.0	+2.2	+3.0	+3.4	+4.7
Springfield, Mo.	520 N	-3.0	-2.8	-2.7	-2.6	-2.6	-1.7	-0.8	-0.5	+0.4	+0.4	+0.6	-0.6	0.0	+0.3	+0.3	+1.1	+1.7	+2.7	+3.4	+5.3	+6.5	+6.7	+6.4	+7.0
Means	**464**	**-1.5**	**-1.0**	**-0.7**	**-0.7**	**-0.3**	**0.0**	**+0.5**	**+0.8**	**+0.8**	**+1.1**	**+0.7**	**+0.2**	**0.0**	**-0.1**	**0.0**	**0.0**	**+0.4**	**+0.7**	**+1.0**	**+1.9**	**+2.5**	**+2.5**	**+2.8**	**+3.5**
6. Pensacola	65 S	-3.0	-2.9	-2.2	-1.8	-0.3	+0.2	+0.2	+0.7	+0.5	0.0	+0.2	0.0	0.0	-0.2	-0.1	+0.5	+1.5	+3.0	+3.2	+3.6	+4.3	+5.0	+5.5	+6.0
Kitty Hawk	100 S	-4.0	-2.0	-1.0	0.0	0.0	0.0	0.0	+1.0	+1.0	+1.0	+1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	+1.0	+1.0	+2.0	+2.0	+3.0	+3.0
Hatteras	100 S	-3.6	-2.4	-1.6	-0.6	+0.2	+0.4	+1.6	+1.9	+2.4	+1.6	+0.9	+0.4	0.0	-0.6	-1.6	-1.0	+0.7	+3.4	+5.4	+6.2	+6.6	+5.9	+5.2	+4.7
Means	**88**	**-3.5**	**-2.4**	**-1.6**	**-0.8**	**0.0**	**+0.2**	**+0.6**	**+1.2**	**+1.3**	**+0.9**	**+0.7**	**+0.1**	**0.0**	**-0.3**	**-0.6**	**-0.2**	**+0.7**	**+2.1**	**+3.2**	**+3.6**	**+4.3**	**+4.3**	**+4.6**	**+4.6**
7. Wilmington	110 S	-7.9	-7.5	-6.9	-6.1	-4.9	-2.9	-1.9	-0.9	+0.1	+0.5	+0.5	+0.1	0.0	-0.5	-0.7	-0.7	+0.1	+1.1	+2.1	+4.3	+4.9	+6.4	+7.8	+8.7
Charleston	125 S	-4.7	-4.1	-3.3	-2.7	-2.4	-1.6	-0.4	-0.1	+0.8	+0.8	+0.7	+0.2	0.0	-0.1	-0.1	+0.1	+1.5	+3.5	+5.1	+6.7	+6.7	+8.6	+11.3	+11.3
Savannah	158 S	-6.3	-5.3	-4.6	-3.7	-2.3	-0.9	-0.3	+0.2	+0.7	+1.0	+0.8	+0.5	0.0	0.0	-0.3	+0.5	+2.0	+3.2	+3.7	+4.9	+6.4	+7.2	+8.2	+9.2
Means	**131**	**-6.3**	**-5.6**	**-4.9**	**-4.2**	**-3.2**	**-1.8**	**-0.9**	**-0.3**	**+0.5**	**+0.8**	**+0.7**	**+0.3**	**0.0**	**-0.2**	**-0.4**	**0.0**	**+1.2**	**+2.6**	**+3.6**	**+5.3**	**+6.0**	**+7.4**	**+9.1**	**+9.7**
8. Jacksonville	240 S	-5.7	-5.1	-4.3	-1.9	-1.1	+0.1	+0.1	+0.2	+0.7	+0.9	+0.8	+0.7	0.0	0.1	+0.2	+1.5	+1.6	+2.7	+3.1	+2.9	+3.7	+4.5	+4.1	+6.0
Tampa	380 S	-2.9	-2.9	-2.9	-2.0	-2.0	-2.0	-1.9	-1.0	-1.0	-0.5	0.0	0.0	0.0	-0.5	0.0	+1.0	+2.0	+2.0	+2.2	+4.0	+4.1	+5.5	+6.0	+7.0
Means	**310**	**-4.3**	**-4.0**	**-3.6**	**-2.0**	**-1.6**	**-1.0**	**-0.9**	**-0.4**	**-0.2**	**+0.2**	**+0.4**	**+0.4**	**0.0**	**-0.3**	**+0.1**	**+1.3**	**+1.8**	**+2.4**	**+2.7**	**+3.5**	**+3.9**	**+5.0**	**+5.1**	**+6.5**
9. Jupiter	500 S	-0.2	-0.2	+0.4	+0.5	+0.6	+0.8	+0.8	+0.8	+0.8	+0.6	+0.5	+0.3	0.0	0.0	+0.3	+1.3	+3.6	+3.0	+3.6	+4.0	+4.3	+3.8	+3.8	+4.8
Key West*	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Means	......	-2.8	-2.5	-2.3	-1.9	-1.4	-0.9	-0.3	+0.2	+0.6	+0.8	+0.6	+0.2	0.0	-0.1	0.0	+0.4	+1.0	+1.9	+2.7	+3.6	+4.4	+4.8	+5.1	+5.4
Shadow variations	......	......	......	......	......	......	......	......	......	0.0	0.0	-0.9	-1.9	-2.2	-2.4	-3.1	-3.4	-3.3	-2.8	-1.4	-0.6	0.0	0.0	......	......

*A local rain occurred which rendered the record inapplicable.

CHART 8.

Temperature variations.

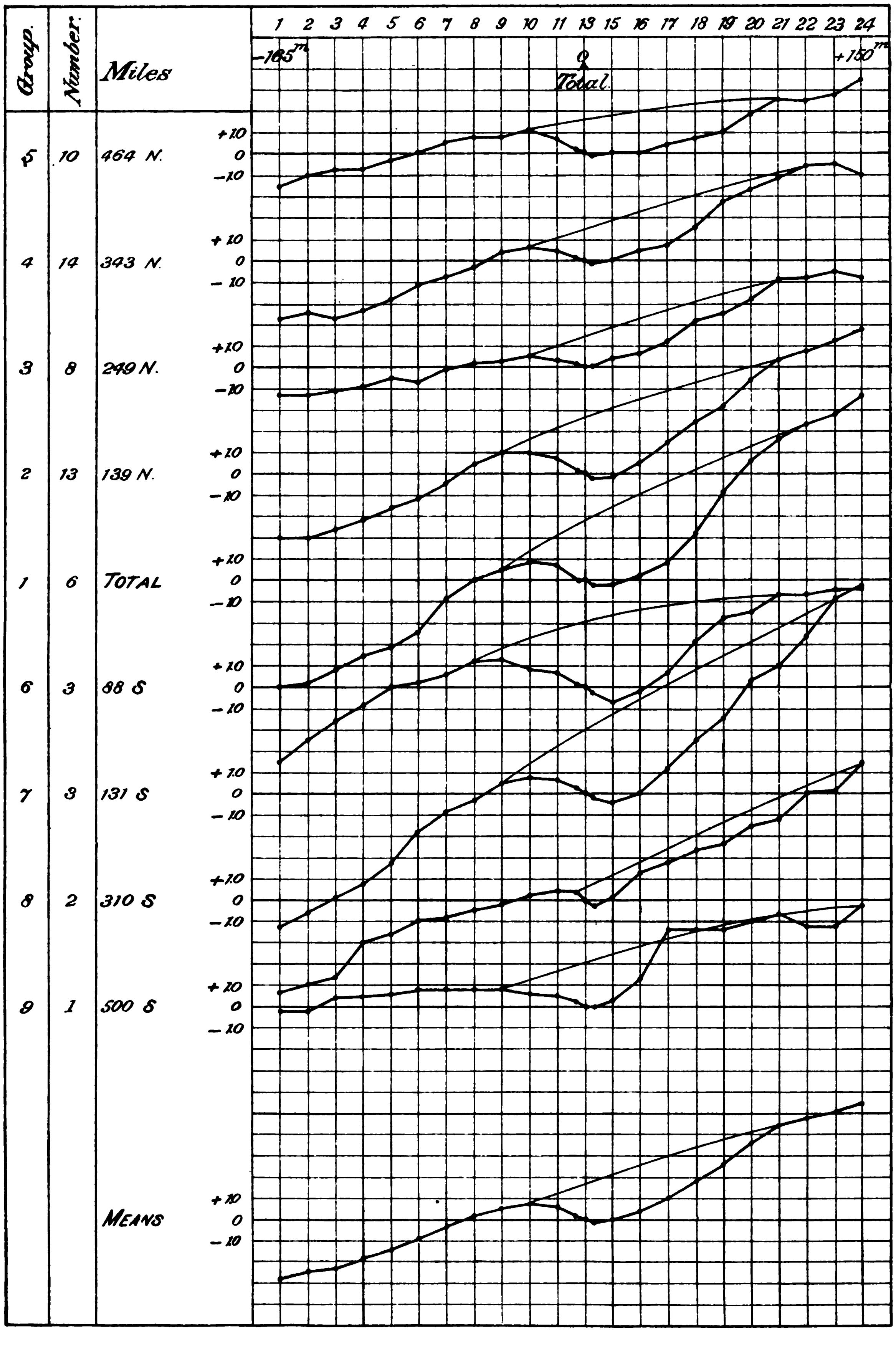


TABLE 6.—*Vapor pressure variations during the total eclipse of May 28, 1900.*

[Referred to the vapor pressure at the moment of totality.]

Station	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
1. New Orleans	0	.000	.000	.000	−.026	−.026	−.026	.000	.000	−.050	.000	.000	.000	.000	.000	.000	.000	.000	.000	.000	−.026	−.026	−.026	−.050	−.076
Raleigh	6 N	−59	−59	−59	−59	−45	−45	−45	−30	−15	0	+16	+33	.000	+33	+16	+16	0	+16	+16	−15	−15	−30	−45	−30
Norfolk	15 N	−31	−31	−31	−16	0	0	+51	+32	+51	+33	+33	−16	.000	+17	+17	+33	+51	+88	+51	+69	+33	+17	+69	+51
Mobile	25 S	0	0	0	0	0	0	0	0	0	0	0	0	.000	0	−16	0	0	0	0	0	0	0	0	0
Charlotte	25 N	15	−15	−15	−15	0	−29	0	0	−15	−15	0	−15	.000	−15	−15	0	+15	−15	−15	0	0	−29	+15	+15
Montgomery	27 N	−40	−40	−40	−40	−40	−40	−40	−20	−20	−20	0	0	.000	0	0	+43	+21	+43	+43	+43	+43	+43	0	+21
Means	**16**	**−24**	**−24**	**−24**	**−26**	**−19**	**−23**	**−6**	**−3**	**−8**	**0**	**+8**	**0**	**.000**	**+6**	**0**	**+15**	**+15**	**+22**	**+16**	**+12**	**+6**	**−4**	**−2**	**−3**
2. Atlanta	40 N	−72	−72	−72	−72	−59	−45	−30	−45	−30	−30	−15	0	.000	0	0	0	0	0	+16	0	0	+32	+16	+32
Meridian	95 N	−68	−89	−68	−89	−68	−46	−46	−24	−24	−24	0	0	.000	0	0	0	+23	0	0	−68	−24	−46	−46	−98
Lynchburg	110 N	−64	−64	−49	−64	−32	−64	−79	−26	−6	−26	+57	−16	.000	−16	0	−16	−33	−16	+18	−33	−33	−33	−16	−33
Galveston	125 N	0	0	0	−25	0	0	0	+25	0	0	+25	0	.000	0	0	+25	+25	+25	+51	+51	+25	+78	+25	+51
Atlantic City	135 N	+15	+15	+15	0	0	0	0	0	0	0	0	0	.000	0	0	0	0	0	0	0	+15	+15	+15	+15
Corpus Christi	140 N	+25	+25	−25	+25	0	−25	0	−25	0	0	0	+25	.000	0	−25	0	0	+25	+25	0	+25	+51	+25	+25
Chattanooga	140 N	+15	+15	+15	+31	+31	−15	0	0	0	0	−15	−15	.000	0	0	+15	+48	+48	+64	+31	−57	−57	−15	0
Vicksburg	155 N	−46	−46	−46	−46	−46	−46	−24	−24	0	0	0	0	.000	0	0	0	+23	0	0	0	0	0	−24	−24
Knoxville	160 N	−16	−16	−16	0	+18	0	−16	0	−16	−33	0	0	.000	−16	0	0	0	0	−16	+36	+18	−49	−16	−64
Washington	160 N	−27	−27	−40	−27	−27	−27	−14	−27	−14	−27	−14	−14	.000	−14	0	0	−14	−14	0	+15	+15	+15	+30	+15
Baltimore	180 N	−51	−51	−51	−39	+14	−51	−51	−51	−13	−26	−26	−13	.000	0	0	−13	−13	0	0	+14	+44	+61	+75	+75
Nantucket	180 N	0	+12	+12	+12	+12	+12	+24	+12	+24	0	0	0	.000	−23	−23	−23	−23	−23	−33	−23	−44	−44	−23	−23
Philadelphia	190 N	−49	−33	−49	−33	−33	−33	−33	−49	−49	−16	−16	−16	.000	−16	−16	−16	0	−16	−16	−16	−16	−16	−16	−16
Means	**139**	**−26**	**−25**	**−25**	**−25**	**−15**	**−26**	**−21**	**−18**	**−10**	**−14**	**−0**	**−4**	**.000**	**−7**	**−5**	**−2**	**+3**	**+2**	**+8**	**+1**	**−2**	**+1**	**+2**	**−3**
3. Block Island	210 N	+24	0	0	−12	0	−12	−12	−12	−12	0	−12	0	.000	0	0	0	0	0	0	−12	−12	−12	−23	−23
New York	220 N	−15	−27	−14	−27	−14	−27	−14	−14	0	0	0	0	.000	0	+15	+15	0	0	0	0	0	+15	+15	−27
New Haven	240 N	+89	+62	+75	+62	+75	+62	+75	+62	+62	+89	+36	+12	.000	0	+12	0	0	−22	−22	−12	−32	−21	−21	0
Harrisburg	260 N	−42	0	−15	−68	−42	−29	+15	−15	+15	+15	−15	−29	.000	0	−29	0	−42	−42	−29	−42	−15	−29	−15	−42
San Antonio	260 N	0	0	−24	−24	−24	−46	0	0	−24	0	0	0	.000	0	0	0	−46	0	−24	−46	−24	−24	−46	−68
Nashville	260 N	−71	−55	−55	−55	−71	−71	−37	−55	−19	−19	−19	0	.000	0	−19	−37	0	−55	−55	−55	−19	−55	−19	−37
Shreveport	260 N	0	0	0	0	0	0	0	0	0	0	0	0	.000	0	+24	0	0	0	0	+24	+24	−22	−22	0
Boston	280 N	+20	+10	+10	+10	+10	+20	+10	+10	0	0	+10	0	.000	0	0	0	−9	0	−9	−9	−9	−18	−18	−9
Means	**249**	**+1**	**−1**	**−8**	**−14**	**−8**	**−13**	**+5**	**−3**	**+3**	**+11**	**0**	**−2**	**.000**	**0**	**0**	**−3**	**−12**	**−15**	**−17**	**−19**	**−11**	**−21**	**−19**	**−26**
4. Palestine	300 N	−22	−43	−43	−83	−22	−22	−43	−43	0	0	+22	+22	.000	0	0	0	0	0	+22	+22	0	+22	+22	0
Parkersburg	300 N	−17	0	0	+18	+18	+18	0	−18	0	0	0	0	.000	0	0	0	−18	0	0	−18	+56	+96	+39	+17
Lexington	300 N	−71	−71	−71	−55	−55	−71	−71	−47	−19	−37	0	−18	.000	−18	−18	−37	−19	−19	0	−37	−37	+19	0	0
Memphis	300 N	0	0	+22	+22	+22	+22	+22	−21	+22	+22	+22	+22	.000	+22	+22	+22	+22	+22	+44	+22	+22	+22	0	−21
Pittsburg	335 N	+17	0	+17	0	0	+17	0	+17	0	0	−16	+51	.000	0	0	+17	0	+33	+17	+33	0	+69	0	+17
Little Rock	340 N	−63	−43	−43	−63	−43	−63	−43	−43	−43	−43	0	0	.000	−22	−22	+46	0	0	0	−43	−43	+46	+46	+22
Albany	345 N	+21	+21	+21	+21	+10	+21	+33	+33	0	+10	−11	−11	.000	−11	−11	0	+45	+10	0	+21	+21	−11	+10	+21
Louisville	350 N	−38	−38	−56	−38	−56	−56	−38	−19	−38	0	0	0	.000	0	0	0	−19	+20	+20	0	0	0	0	+20

TABLE 6.—*Vapor pressure variations during the total eclipse of May 28, 1900*—Continued.

Station	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
4. Binghamton	350 N	− 30	− 45	− 15	− 45	0	+ 16	+ 16	+ 16	+ 16	0	0	0	.000	0	+ 33	0	+ 16	+ 16	+ 16	+ 16	+ 33	+ 33	+ 16	− 15
Portland	360 N	+ 31	+ 31	+ 49	+ 31	+ 31	+ 15	+ 15	+ 7	+ 31	+ 7	0	0	.000	0	0	+ 15	+ 15	+ 15	+ 15	+ 31	+ 39	+ 23	+ 31	+ 7
Cincinnati	370 N	0	− 19	− 38	− 19	− 19	0	0	− 19	− 19	0	− 19	0	.000	− 19	− 19	− 19	0	− 19	− 19	− 19	− 19	0	0	0
Cairo	380 N	+ 22	+ 22	0	0	0	0	− 22	− 22	− 22	− 22	0	0	.000	0	− 22	− 22	0	0	+ 22	+ 46	+ 46	+ 22	+ 22	+ 46
Columbus	380 N	0	0	0	0	0	+ 18	+ 18	+ 18	+ 18	+ 18	+ 18	0	.000	+ 18	0	0	0	0	0	+ 18	0	0	0	+ 18
Eastport	390 N	− 43	− 35	− 27	0	0	− 9	0	0	0	0	0	0	.000	0	0	0	0	+ 10	+ 20	− 20	+ 10	+ 20	+ 20	+ 20
Means	**348**	**− 14**	**− 15**	**− 13**	**− 15**	**− 8**	**− 7**	**− 8**	**− 10**	**− 4**	**− 3**	**+ 1**	**+ 5**	**.000**	**− 2**	**− 3**	**+ 3**	**+ 3**	**+ 6**	**+ 11**	**+ 5**	**+ 9**	**+ 26**	**+ 15**	**+ 11**
5. Northfield	425 N	− 47	− 47	− 47	− 36	− 47	− 36	− 47	− 24	− 24	− 24	0	0	.000	− 12	0	0	− 12	0	− 36	− 24	− 24	− 36	− 36	− 24
Cleveland	445 N	+ 17	+ 17	+ 17	+ 17	+ 33	+ 33	+ 17	+ 33	+ 17	0	+ 17	0	.000	0	+ 17	+ 33	+ 33	+ 33	+ 33	+ 17	+ 17	+ 33	+ 33	+ 33
Erie	450 N	− 33	− 33	− 33	− 17	− 17	− 17	− 17	0	0	0	0	0	.000	0	0	0	0	0	0	− 17	0	0	0	+ 34
Oswego	450 N	+ 15	+ 31	+ 31	+ 31	+ 31	+ 31	+ 31	+ 49	+ 49	+ 31	+ 31	+ 31	.000	0	+ 15	+ 31	+ 15	+ 15	+ 31	+ 15	+ 15	0	0	− 15
Indianapolis	450 N	+ 39	+ 39	+ 39	+ 19	0	+ 19	0	0	0	+ 19	+ 19	+ 19	.000	+ 19	+ 19	+ 19	+ 19	+ 19	+ 38	+ 19	0	+ 19	+ 19	+ 38
Rochester	460 N	0	+ 16	+ 49	+ 49	+ 49	+ 49	+ 49	+ 16	+ 16	0	+ 16	0	.000	+ 16	0	− 15	− 15	− 15	0	+ 16	+ 16	+ 33	+ 33	+ 16
Sandusky	465 N	− 18	− 18	− 18	− 18	− 18	− 18	0	0	0	0	0	0	.000	0	+ 18	0	0	0	0	+ 18	+ 18	+ 18	+ 18	+ 18
Buffalo	465 N	− 16	0	− 16	0	− 16	− 31	− 31	− 16	− 16	− 16	0	0	.000	+ 17	+ 17	+ 17	+ 33	0	0	+ 17	0	+ 17	+ 17	+ 17
Abilene	470 N	− 19	0	0	0	0	0	0	0	+ 20	0	0	0	.000	0	0	0	+ 20	+ 40	+ 20	+ 20	+ 20	+ 20	+ 40	+ 40
St. Louis	500 N	+ 85	+ 41	+ 20	0	− 20	+ 20	− 20	0	+ 20	0	0	0	.000	0	0	0	− 20	0	0	0	0	0	0	− 20
Springfield, Mo.	520 N	− 40	− 40	− 20	− 20	− 20	− 40	− 20	− 20	− 40	− 20	0	+ 19	.000	0	0	0	+ 21	+ 21	0	+ 21	+ 21	+ 21	0	0
Means	**464**	**− 2**	**+ 1**	**+ 2**	**+ 2**	**− 2**	**+ 1**	**+ 3**	**+ 3**	**+ 4**	**− 1**	**+ 8**	**+ 6**	**.000**	**+ 4**	**+ 8**	**+ 8**	**+ 9**	**+ 10**	**+ 8**	**+ 9**	**+ 8**	**+ 11**	**+ 11**	**+ 12**
6. Pensacola	65 S	0	0	0	+ 25	+ 25	+ 25	0	+ 25	0	+ 25	0	0	.000	− 25	− 25	− 48	− 48	− 48	− 48	− 48	− 48	− 48	− 48	− 48
Kitty Hawk	100 S	0	+ 33	+ 51	+ 69	+ 69	+107	+ 69	+ 88	+ 88	+ 88	+ 88	0	.000	+ 33	+ 69	+ 69	+ 69	+ 69	+ 51	+ 51	+ 51	+ 51	+ 51	+ 51
Hatteras	100 S	− 16	0	0	− 16	− 31	− 31	0	− 16	0	+ 33	+ 17	0	.000	0	+ 17	+ 17	0	0	0	0	+ 32	0	− 31	− 46
Means	**88**	**− 5**	**+ 11**	**+ 17**	**+ 26**	**+ 21**	**+ 34**	**+ 23**	**+ 32**	**+ 29**	**+ 49**	**+ 85**	**0**	**.000**	**+ 3**	**+ 20**	**+ 18**	**+ 7**	**+ 7**	**+ 1**	**+ 1**	**+ 12**	**+ 1**	**− 9**	**− 14**
7. Wilmington	110 S	− 30	− 44	− 30	− 44	− 57	− 57	− 30	− 44	− 44	− 57	− 57	− 30	.000	0	+ 15	0	− 15	0	+ 15	+ 15	− 30	0	− 15	0
Charleston	125 S	− 15	− 15	0	− 15	− 15	− 15	− 15	− 30	0	− 15	0	− 15	.000	0	0	0	+ 16	− 15	− 15	− 15	− 15	0	15	− 15
Savannah	158 S	+ 33	0	0	0	0	0	+ 18	+ 18	+ 36	+ 55	0	+ 18	.000	+ 18	+ 18	+ 55	+ 36	+ 18	− 16	0	− 49	− 64	− 64	− 64
Means	**131**	**− 4**	**− 20**	**− 10**	**− 20**	**− 24**	**− 24**	**− 9**	**− 19**	**− 3**	**− 6**	**− 19**	**− 9**	**.000**	**+ 6**	**+ 11**	**+ 18**	**+ 12**	**+ 1**	**− 5**	**0**	**− 31**	**− 21**	**− 31**	**− 26**
8. Jacksonville	240 S	+ 59	+ 39	+ 59	+ 39	+ 39	+ 39	+ 19	+ 19	+ 19	0	+ 19	0	.000	0	0	0	0	+ 19	− 37	− 37	− 55	− 55	− 55	− 19
Tampa	380 S	− 44	− 44	− 44	− 44	− 22	− 22	− 22	− 22	− 22	− 22	0	0	.000	− 22	0	− 22	0	0	0	− 22	− 22	+ 24	− 44	− 44
Means	**310**	**+ 8**	**− 3**	**+ 8**	**− 3**	**+ 9**	**+ 9**	**− 2**	**− 2**	**− 2**	**− 11**	**+ 10**	**0**	**.000**	**− 11**	**0**	**− 11**	**0**	**+ 10**	**− 19**	**− 30**	**− 39**	**− 16**	**− 50**	**− 32**
9. Jupiter	500 S	0	0	0	0	0	0	+ 25	+ 25	+ 25	+ 25	+ 25	+ 25	.000	0	0	+ 25	+ 50	+ 50	+ 50	+ 25	+ 76	+ 76	+ 25	+ 50
Means	....	− 12	− 12	− 10	− 13	− 8	− 10	− 5	− 5	− 1	0	+ 4	+ 1	.000	− 1	+ 1	+ 4	+ 5	+ 9	+ 5	+ 1	+ 1	+ 5	0	− 2
Shadow variations	....	....	....	....	....	....	....	....	....	....	.000	−.002	−.004	−.005	−.006	−.007	−.007	−.006	−.003	.000	....	....	....	....	....

CHART 9. **Vapor pressure variations.**

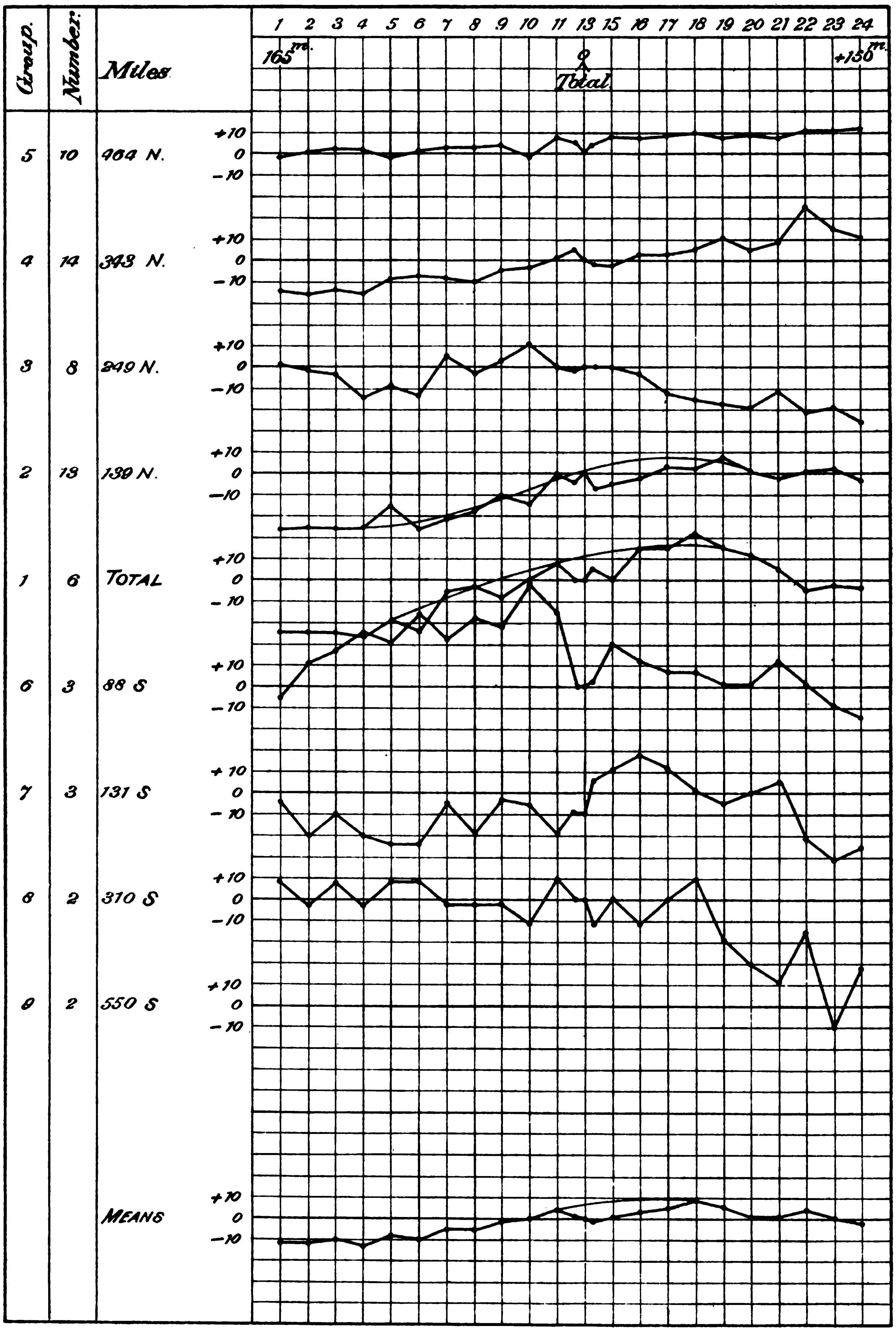


TABLE 7.— *Wind velocities during the total eclipse of May 28, 1900.*

Station	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
1. New Orleans	0	2	2	2	2	4	4	4	2	2	3	3	3	3	3	4	4	3	7	8	5	8	6	7	7
Raleigh	6 N	3	1	0	1	1	3	4	3	3	6	4	3	4	3	4	5	6	6	6	7	7	8	7	5
Norfolk	15 N	3	3	3	2	3	3	2	2	2	3	3	5	5	4	4	4	6	6	6	8	8	10	10	11
Mobile	25 S	2	3	4	4	4	5	5	3	3	4	4	4	3	3	3	3	5	3	4	4	5	5	6	6
Charlotte	25 N	7	7	7	6	4	4	4	6	8	7	8	8	8	7	6	6	7	8	9	9	10	9	9	8
Montgomery	27 N	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	1	3	4
Mean *v*	16 N	3.0	2.7	2.8	2.7	2.8	3.3	3.3	2.8	3.2	4.0	3.8	4.0	4.0	3.5	3.7	3.8	4.7	5.2	5.7	5.8	6.7	6.5	7.0	6.8
2. Atlanta	40 N	11	11	12	12	10	9	10	9	9	10	11	8	8	8	8	6	6	9	8	8	8	7	10	8
Meridian	95 N	1	1	1	1	1	1	1	1	1	1	2	3	3	3	3	3	2	2	2	3	3	3	6	6
Lynchburg	110 N	3	1	1	1	1	1	1	1	1	2	2	2	2	3	1	1	1	1	3	2	2	2	2	2
Galveston	125 N	2	2	2	2	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	1	1	6	5	8
Atlantic City	135 N	4	4	4	5	6	8	6	6	6	9	7	7	6	6	6	7	6	5	5	5	8	6	8	7
Corpus Christi	140 N	7	6	6	5	5	5	4	3	3	4	4	4	4	4	4	3	2	3	3	4	5	6	6	6
Chattanooga	140 N	2	1	1	1	1	2	2	2	2	1	1	1	1	1	1	1	1	1	1	1	1	3	7	5
Vicksburg	155 N	6	6	6	7	6	6	6	7	6	7	5	5	5	5	4	3	3	3	3	4	5	5	6	5
Knoxville	160 N	4	5	5	4	3	2	3	3	3	4	5	6	6	6	5	4	4	7	10	6	7	10	11	12
Washington	160 N	3	3	3	3	3	3	3	3	4	4	4	4	4	4	3	3	3	4	6	6	5	5	5	5
Baltimore	180 N	0	2	3	4	4	4	3	3	4	4	4	3	3	3	3	3	3	3	3	3	2	3	3	3
Nantucket	180 N	19	18	16	18	15	20	19	20	17	20	20	18	19	18	20	20	20	17	16	16	20	21	24	21
Philadelphia	190 N	1	1	1	1	1	1	1	1	2	3	5	7	6	7	9	10	10	9	10	12	13	12	13	13
Mean *v*	139 N	4.9	4.6	4.7	5.0	4.5	5.1	4.9	4.9	4.8	4.9	5.6	5.3	5.2	5.3	5.2	4.9	4.6	5.0	5.4	5.4	6.1	7.1	7.8	7.6
3. Block Island	210 N	23	31	30	29	24	24	22	23	22	22	24	23	23	24	24	25	27	25	27	29	27	28	29	27
New York	220 N	20	28	25	26	26	24	26	27	24	25	27	29	27	23	26	16	23	20	22	14	11	11	15	12
New Haven	240 N	10	10	9	12	11	11	18	12	12	14	15	14	14	10	12	12	12	12	12	12	12	12	12	11
Harrisburg	260 N	2	2	2	2	2	2	2	1	1	4	4	4	4	4	2	4	3	3	3	5	5	6	9	12
San Antonio	260 N	2	2	2	2	2	2	2	2	2	2	2	1	0	0	1	1	2	2	4	5	6	7	7	5
Nashville	260 N	2	2	2	2	2	2	2	2	2	3	3	3	3	3	2	2	2	5	6	5	5	8	8	6
Shreveport	260 N	5	5	5	4	4	4	5	9	7	4	4	4	4	3	3	2	5	5	6	6	5	5	9	7
Boston	280 N	13	12	13	15	15	18	15	16	15	16	13	12	10	11	12	12	13	13	15	12	18	11	15	14
Mean *v*	249 N	9.6	11.5	11.0	11.5	10.8	10.9	11.5	11.5	10.6	11.3	11.4	11.3	10.6	9.8	10.3	9.3	10.9	10.6	11.9	11.0	11.1	11.0	13.0	11.8
4. Palestine	300 N	5	5	5	5	4	4	4	6	7	7	7	7	5	4	5	4	4	5	7	6	7	10	8	9
Parkersburg	300 N	0	0	0	0	0	0	0	2	3	3	3	2	2	2	2	2	5	8	7	4	2	2	2	2
Lexington	300 N	7	7	7	7	7	7	7	9	9	9	8	7	7	7	7	7	8	11	11	10	12	14	14	14
Memphis	300 N	7	6	6	7	8	8	10	9	9	10	9	8	10	10	11	15	12	14	10	11	12	14	12	8
Pittsburg	335 N	1	1	1	1	2	2	2	3	4	4	3	5	5	4	4	2	3	4	5	4	4	8	4	5
Little Rock	340 N	4	3	2	2	2	4	0	4	2	2	4	3	3	5	6	6	3	6	6	9	10	10	6	9
Albany	345 N	6	8	6	8	8	8	9	8	5	9	8	8	9	8	8	8	9	8	10	8	6	8	8	8
Louisville	350 N	6	5	5	6	8	5	5	6	7	6	5	4	4	4	4	4	4	6	5	7	8	8	10	9
Binghamton	350 N	3	4	4	2	6	4	4	4	4	2	4	6	6	3	3	3	4	3	5	8	7	7	4	8

TABLE 7.—*Wind velocities during the total eclipse of May 28, 1900*—Continued.

Station	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
4. Portland	360 N	12	10	9	9	10	11	13	11	10	10	9	11	10	11	8	8	8	8	8	8	9	8	10	12
Cincinnati	370 N	2	2	2	4	4	5	4	3	3	3	6	11	8	8	7	7	8	6	5	8	8	7	8	5
Cairo	380 N	4	4	7	7	7	4	6	7	6	6	4	4	4	4	5	3	3	6	7	7	6	8	10	9
Columbus	380 N	7	7	5	5	2	2	2	6	5	3	5	5	5	5	5	5	6	5	4	7	7	7	7	6
Eastport	390 N	7	10	7	9	11	11	8	8	9	7	6	5	3	3	3	6	4	4	7	12	12	11	7	6
Mean *v*	343 N	5.1	5.[illegible]	4.7	5.1	5.6	4.7	5.3	6.1	5.9	5.8	5.8	6.1	5.8	5.6	5.6	5.7	5.8	6.7	6.9	7.8	7.9	8.7	7.9	7.9
5. Northfield	425 N	14	13	20	20	20	13	13	12	11	12	9	8	5	5	6	5	5	8	9	9	11	11	8	12
Cleveland	445 N	8	7	10	7	8	6	6	3	5	4	4	5	5	6	8	13	17	19	20	14	13	12	10	9
Erie	450 N	6	6	6	7	7	8	7	6	6	6	5	6	6	6	6	6	4	5	5	6	4	4	1	2
Oswego	450 N	3	3	3	4	4	4	3	4	4	3	3	5	5	7	5	5	8	6	8	9	8	9	10	9
Indianapolis	450 N	11	6	4	7	12	9	6	9	8	13	13	15	14	14	15	9	7	10	6	5	7	5	6	5
Rochester	460 N	3	3	3	3	3	3	4	3	5	4	5	5	5	5	5	5	6	6	6	9	8	9	8	8
Sandusky	465 N	8	4	4	4	5	4	4	5	4	4	5	4	4	5	5	8	8	7	7	5	4	4	2	2
Buffalo	465 N	4	6	8	9	8	8	7	6	5	6	5	5	6	7	8	6	2	3	3	3	4	4	3	4
Abilene	470 N	5	6	12	11	12	12	12	14	12	12	9	10	9	12	12	15	16	12	10	10	14	12	11	11
St. Louis	500 N	4	4	6	6	12	13	6	7	9	8	6	5	5	6	8	8	7	9	10	10	11	7	8	6
Springfield	520 N	4	6	7	6	6	6	8	8	6	6	7	6	6	8	6	8	8	7	8	7	12	7	8	7
Mean *v*	464 N	6.4	5.8	7.5	7.6	8.8	7.8	6.9	7.0	6.8	7.1	6.5	6.7	6.4	7.4	7.6	8.0	8.0	8.4	8.4	7.9	8.7	7.6	6.8	6.8
6. Pensacola	65 S	6	5	8	5	7	5	10	7	10	9	12	10	12	14	12	10	8	12	12	15	10	12	11	14
Kitty Hawk	100 S	0	0	0	0	1	0	6	5	4	3	0	0	1	0	0	4	4	4	4	4	4	4	4	4
Hatteras	100 S	2	2	2	3	2	2	2	2	2	2	2	2	2	2	1	4	4	2	2	2	2	4	6	6
Mean *v*	88 S	2.7	2.3	3.3	2.7	3.3	2.3	6.0	4.7	5.3	4.7	4.7	4.0	5.0	5.3	4.3	6.0	5.3	6.0	6.0	7.0	5.3	6.7	7.0	8.0
7. Wilmington	110 S	5	4	5	6	7	9	9	9	9	8	9	6	6	6	5	4	4	6	4	4	5	10	3	6
Charleston	125 S	6	7	6	8	9	9	8	11	9	8	9	8	7	7	8	8	10	8	8	10	12	14	9	9
Savannah	158 S	3	2	3	4	7	6	7	5	6	6	5	5	5	4	4	3	4	6	7	5	5	4	8	4
Mean *v*	131 S	4.7	4.3	4.7	6.0	7.7	8.0	8.0	8.3	8.0	7.3	7.7	6.3	6.0	5.7	5.7	5.0	6.0	6.7	6.3	6.3	7.3	9.3	6.7	6.3
8. Jacksonville	240 S	5	4	3	3	3	4	5	6	8	9	8	8	6	6	6	6	8	10	9	8	7	6	8	8
Tampa	380 S	5	4	5	5	5	5	5	6	5	6	5	5	5	5	4	3	5	7	10	10	8	7	8	6
Mean *v*	310 S	5.0	4.0	4.0	4.0	4.0	4.5	5.0	6.0	6.7	7.5	6.5	6.5	5.5	5.5	5.0	4.5	6.5	8.5	9.5	9.0	7.5	6.5	8.0	7.0
9. Jupiter	500 S	12	9	10	11	11	9	10	9	10	9	10	10	9	10	10	10	10	12	12	11	11	10	12	10
Key West	600 S	3	5	7	7	8	9	12	12	12	14	8	8	7	6	5	7	6	6	10	10	12	12	11	12
Mean *v*	550 S	7.5	7.0	8.5	9.0	9.5	9.0	11.0	10.5	11.0	11.5	9.0	9.0	8.0	8.0	7.5	8.5	8.0	9.0	11.0	10.5	11.5	11.0	11.5	11.0
Means		5.6	5.6	5.9	6.1	6.4	6.3	6.4	6.6	6.4	6.6	6.6	6.5	6.3	6.3	6.3	6.3	6.6	7.1	7.5	7.5	7.9	8.2	8.3	8.0

CHART 10.

Wind velocity variations.

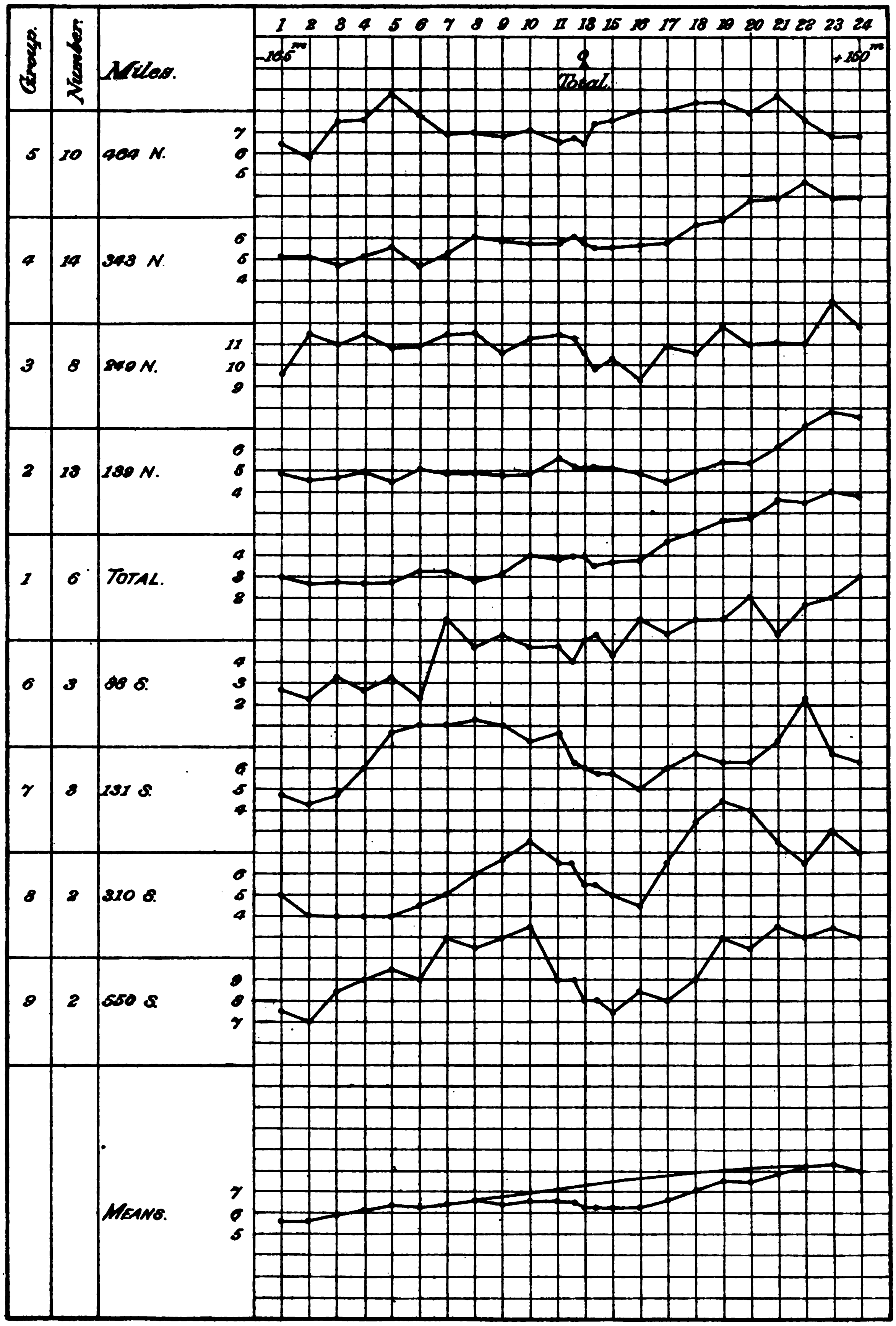


TABLE 8.—*Wind azimuths during the total eclipse of May 28, 1900.*

	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 15	12 −5	13 Total.	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
1. New Orleans	0	180	225	225	225	225	270	225	270	225	225	270	315	225	270	315	270	315	270	270	270	225	225	225	225
Raleigh	6 N	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	90	90	90	135
Norfolk	15 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Mobile	25 S	315	315	315	315	315	315	315	270	270	270	315	315	315	315	315	315	315	315	315	315	315	315	315	315
Charlotte	25 N	180	180	180	180	180	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135
Montgomery	27 N	225	......	225	225	225	225	225	270	270	270	270	270	270	270	270	270	270	270	270	315	315	315	315	315
Mean φ	16 N	203	207	210	210	210	210	203	210	203	203	217	226	210	217	226	217	226	217	217	226	210	210	210	218
2. Atlanta	40 N	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	90	90	135
Meridian	95 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	135	135	135	135	180	135	135	135	135
Lynchburg	110 N	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135
Galveston	125 N	180	180	......	......	......	......	......	315	......	......	......	......	......	......	......	......	270	270	315	270	315	220	270	270
Atlantic City	135 N	135	135	135	135	135	180	180	180	180	135	180	135	180	180	180	180	180	180	180	135	135	135	135	135
Corpus Christi	140 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	225	225	225	225	270	270
Chattanooga	140 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	225	225	225
Vicksburg	155 N	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	180	......	......	180	......	180	......
Knoxville	160 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	135	135	135	180	180	180	180
Washington	160 N	180	180	180	180	180	180	180	180	225	225	180	180	180	180	180	225	225	225	180	180	225	225	225	225
Baltimore	180 N	.....	225	180	180	180	180	180	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	135	225
Nantucket	180 N	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315
Philadelphia	190 N	90	90	90	90	90	90	90	90	180	180	270	270	270	270	270	315	270	270	315	315	315	270	270	315
Mean φ	....	176	180	176	176	176	180	180	187	188	184	191	188	191	191	191	195	297	187	199	195	201	195	197	214
3. Block Island	210 N	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	270
New York	220 N	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	270	315	315	315	315
New Haven	240 N	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315
Harrisburg	260 N	180	180	180	180	180	180	180	180	180	90	90	90	90	90	90	90	90	90	90	315	270	315	315	270
San Antonio	260 N	225	315	315	315	315	315	315	315	315	315	315	315	......	......	315	315	225	225	180	180	180	180	180	180
Nashville	260 N	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	180	135	135	135	135	135	135
Shreveport	260 N	225	225	225	225	225	225	225	225	225	180	180	135	135	135	135	180	180	180	180	180	180	225	225	225
Boston	280 N	315	315	315	315	315	315	315	315	315	315	315	315	360	315	360	315	360	315	315	315	315	315	315	315
Mean φ	249	270	281	281	281	281	281	281	281	281	264	264	259	257	251	264	264	259	242	231	253	253	264	264	253
4. Palestine	300 N	180	180	180	180	180	180	225	225	225	......	180	180	......	180	180	180	180	180	180	135	135	135	135	135
Parkersburg	300 N	......	......	......	......	......	......	......	180	180	225	315	225	225	225	225	225	225	225	225	135	135	180	180	221
Lexington	300 N	225	225	225	180	225	180	180	180	180	180	180	180	180	180	180	180	180	225	225	225	180	225	135	135
Memphis	300 N	180	180	180	180	180	180	135	135	135	135	135	135	135	135	135	180	135	135	135	135	135	135	135	135
Pittsburg	335 N	45	45	45	45	45	45	45	45	90	90	90	45	45	90	90	90	90	135	135	90	90	135	90	180
Little Rock	340 N	135	90	90	90	90	90	......	225	135	135	180	180	180	180	180	225	225	225	225	225	225	225	180	225
Albany	345 N	225	180	180	180	180	180	180	180	180	225	180	180	180	180	180	180	180	180	180	180	180	180	225	225
Louisville	350 N	180	180	180	180	180	180	180	225	180	180	225	225	180	180	180	180	180	180	180	180	180	135	135	135

TABLE 8.—*Wind azimuths during the total eclipse of May 28, 1900*—Continued.

	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total.	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
4. Binghamton	350 N	90	90	90	90	90	90	90	90	90	90	90	45	45	45	45	45	45	45	45	45	45	45	360	315
Portland	360 N	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	270	270
Cincinnati	370 N	180	180	180	135	225	225	225	225	225	225	45	360	360	360	360	360	360	315	315	315	315	270	315	315
Cairo	380 N	135	135	180	225	225	270	270	270	270	270	270	225	225	225	225	225	225	225	225	225	225	180	180	180
Columbus	380 N	225	225	225	315	315	225	180	180	135	135	135	135	135	135	135	135	135	135	135	135	135	90	90	90
Eastport	390 N	315	315	315	315	315	315	315	315	315	315	360	360	360	360	315	270	270	315	315	315	315	315	315	315
Mean φ	343	187	180	183	187	197	190	195	199	190	194	193	199	197	199	197	199	196	202	202	190	186	183	196	206
5. Northfield	425 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180
Cleveland	445 N	180	180	135	135	90	90	135	90	360	315	315	315	315	315	225	225	225	225	225	225	225	225	180	90
Erie	450 N	180	180	180	180	180	180	180	180	180	180	180	180	135	135	135	135	135	135	135	135	135	135	135	135
Oswego	450 N	315	315	360	360	315	315	315	315	315	360	315	360	360	360	360	360	360	360	360	360	360	360	360	360
Indianapolis	450 N	360	360	360	360	135	135	135	135	135	135	180	180	180	180	180	180	180	360	270	315	315	315	315	315
Rochester	460 N	135	135	135	135	135	135	135	135	360	360	360	360	360	360	360	360	315	315	315	315	315	315	315	315
Sandusky	465 N	135	135	135	180	135	225	225	225	225	225	225	225	180	180	180	135	135	135	135	135	135	135	135	180
Buffalo	465 N	180	225	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	135	135	135	135
Abilene	470 N	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	225	180	135	135	135	225	135	180
St. Louis	500 N	180	180	180	135	135	135	180	180	180	180	180	180	180	135	135	135	135	180	135	135	135	90	90	90
Springfield	520 N	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	180	135	135	135
Mean φ	464	205	209	213	213	180	188	196	192	237	237	237	241	233	229	221	217	213	229	213	217	205	205	192	192
6. Pensacola	65 S	315	315	315	315	315	315	270	315	270	315	270	270	270	270	270	270	270	270	270	270	270	270	225	225
Kitty Hawk	100 S	......	......	......	......	135	......	270	180	270	270	225	180	180	180	180	225	225	225	225	225	225	225	225	225
Hatteras	100 S	90	90	90	135	135	135	135	135	135	135	135	135	135	135	135	225	225	225	225	225	270	225	225	270
Mean φ	88	202	203	202	225	195	225	225	210	225	240	210	195	195	195	195	240	240	240	240	240	255	240	225	240
7. Wilmington	110 S	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	45	45	45	90	90
Charleston	125 S	135	90	45	90	90	90	45	90	90	90	90	90	90	90	90	90	45	45	45	45	45	45	45	45
Savannah	158 S	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	90	135	180
Mean φ	131	105	90	75	90	90	90	75	90	90	90	90	90	90	90	90	90	75	75	75	60	60	60	90	105
8. Jacksonville	240 S	270	270	270	270	270	270	270	225	270	270	270	270	270	270	270	270	270	225	225	225	225	225	225	225
Tampa	380 S	315	315	315	315	315	315	315	315	315	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270
Mean φ	310	293	293	292	292	292	292	292	270	292	270	270	270	270	270	270	270	270	248	248	248	248	248	248	248
9. Jupiter	500 S	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315	315
Key West	600 S	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270	270
Mean φ	550	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292	292
Means	....	204	205	209	208	203	205	207	206	215	213	214	215	214	211	207	214	213	210	210	209	206	205	207	213

CHART 11.

Wind azimuth variations.

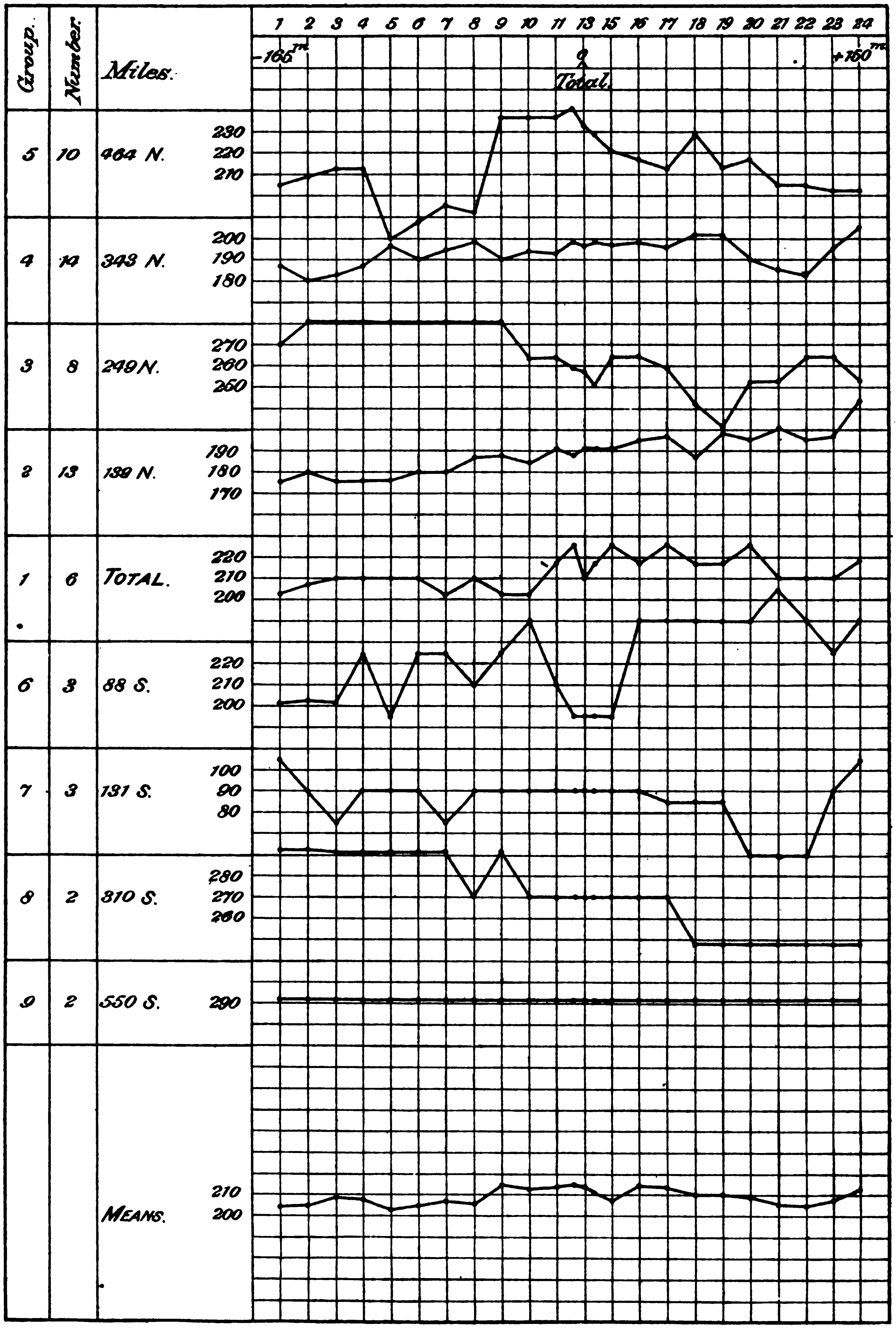


TABLE 9.—*Amount of cloudiness during the total eclipse of May 28, 1900.*

Stations	Dist. Cent.	1 −165	2 −150	3 −135	4 −120	5 −105	6 −90	7 −75	8 −60	9 −45	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105	22 +120	23 +135	24 +150
New Orleans	0	......	1	1	5	5	3	3	2	2	2	1	......	......	......	......	......	......	1	4	6	6	7	6	7
Raleigh	6 N	......	......	......	......	......	......	......	......	......	......	......	......	......	1	1	......	2	1	1	1	1	1	1	1
Norfolk	15 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Mobile	25 S	3	4	4	3	2	1	2	8	5	7	6	4	3	3	5	6	3	3	4	4	4	4	4	4
Charlotte	25 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Montgomery	27 N	3	2	......	......	......	1	1	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Atlanta	40 N	1	......	......	......	......	......	......	......	......	......	2	1	1	......	2	......	1	......	......	......	......	......	......	......
Pensacola	65 S	1	1	1	......	......	......	......	1	2	3	4	4	5	2	3	......	......	......	......	......	......	......	......	......
Meridian	95 N	6	6	6	8	9	9	7	8	6	5	4	3	2	2	1	1	1	1	3	3	2	2	2	2
Kitty Hawk	100 S	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Hatteras	100 S	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Lynchburg	110 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Wilmington	110 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Galveston	125 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Charleston	125 S	5	4	5	5	5	5	5	5	7	7	7	6	6	6	6	6	5	5	5	5	5	5	6	6
Atlantic City	135 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Corpus Christi	140 N	......	......	......	......	......	......	......	2	3	4	1	......	......	......	1	1	1	......	......	1	3	3	3	1
Chattanooga	140 N	1	1	......	......	......	......	1	2	......	......	......	......	1	1	......	2	......	......	......	......	......	......	......	......
Vicksburg	155 N	2	2	1	1	2	1	......	......	......	......	......	1	1	......	......	......	......	......	1	1	2	3	4	4
Savannah	158 S	5	7	5	8	8	8	9	9	8	8	8	8	8	8	8	7	7	7	6	5	5	5	5	6
Knoxville	160 N	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......	......
Washington	160 N	1	1	1	2	6	8	9	10	10	10	10	10	10	7	7	7	6	6	6	6	8	9	10	10
Baltimore	180 N	9	8	8	6	4	4	6	4	3	4	8	8	7	7	8	8	9	6	5	5	5	4	5	4
Nantucket	180 N	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
Philadelphia	190 N	......	......	......	......	......	......	......	......	......	......	1	5	7	7	7	5	5	6	4	3	4	4	7	8
Block Island	210 N	10	10	10	10	9	10	9	9	10	10	10	10	10	10	10	10	10	10	10	10	9	8	7	8
Means	....	**2.2**	**2.2**	**2.0**	**2.2**	**2.3**	**2.3**	**2.4**	**2.7**	**2.7**	**2.7**	**2.8**	**2.7**	**2.7**	**2.5**	**2.6**	**2.4**	**2.3**	**2.2**	**2.3**	**2.3**	**2.5**	**2.5**	**2.7**	**2.7**

TEMPERATURE.

Precisely the same method was employed in discussing the temperature observations in Table 5 and on Chart 8 as for the pressure variations. In marked contrast with the uncertainty pertaining to the pressure, the variations of temperature are very clearly defined. The course of the usual diurnal range is interrupted at No. 9, 45 minutes before totality, so that the curve drops to a minimum at No. 15, or even a few minutes earlier, namely, 10 or 15 minutes after totality, and recovers its normal course at No. 22, which is 2 hours after the moment of totality. The greatest lowering of the temperature is about 3°.5 in the total shadow, and this falls away irregularly to the north and the south. The local rates of absorption might perhaps be studied at the several stations by plotting the residuals Δt, but I have not attempted to carry out this differential work, though it might have given us some information regarding the integral absorption of the upper layers of the atmosphere.

VAPOR PRESSURE.

The variations of the vapor pressure are given on Table 6 and Chart 9. There is very great irregularity among the groups when compared with one another, but the means show that we must admit a decrease of the vapor tension of about 0.01 inch at the time of the maximum cooling of the air. This does not agree with the difference of saturation which would correspond with a change of 3° in the dew-point taken between 50° and 60° on the average, for that would be 0.05 inch. However, for a relative humidity of 70 per cent this becomes 0.035 inch. In the rapid motion of the shadow there was apparently a lack of sufficient time for the vapor contents to completely readjust themselves to the new temperatures, but this is evidently a cause for the production of a multitude of minute adjustment currents, especially on the edges of the umbra, which would produce in that place a series of mixing and turbulent minor movements of the air. Indeed, there should be set in motion a rapid interchange of small currents between the total shadow and the adjacent atmosphere, where the temperature and the vapor tension seek a new equilibrium, and this turbulent action along the edge of the umbral cone throughout the depth of the atmosphere is well calculated to produce what is known as "optical obscuration" or darkening due to such currents. The rays of light from the sun struggling through these congested minor currents would undergo all sorts of anomalous refractions and reflections, and could reach the observer only in the form of fluttering waves, partly dark and partly light, such as are observed in the well-known eclipse shadow bands. An object seen through such a mixing layer would have the appearance of one intermittently visible through a mechanical obstruction pierced with holes, as through the leaves of a tree, where the form of the object is thrown down in a great number of detached images. This seems to be the cause of the light spaces in the shadow bands, and in Chapter 3 it will be shown that the object seen in this way is the changing crescent of the disappearing or the appearing solar disk. Hence I have concluded that the shadow bands are simply a meteorological phenomenon, and have nothing to do with the diffraction of light around the edge of the moon.

THE WIND VELOCITY.

The wind velocities are recorded on Table 7 and Chart 10. The mean result is that the wind falls about 1 mile per hour on an average velocity of 6 miles. The groups 7, 8, and 9 show larger ranges than this, possibly 2 or 3 miles per hour. It should be noted, however, that all these stations are located on the South Atlantic or Florida coasts, and that there is probably something like a sea-breeze effect involved in this larger range. The winds during the eclipse blew from the south generally, as is seen by inspecting Table 8. This diminution of the wind velocity means a decrease in the current of air directed northward, which would be caused by imposing a southward component upon the northward stream. This remark seems to suggest that the wind variation is simply like an ordinary nocturnal effect, when the continental air, being chilled by the shadow, tends to flow toward the ocean areas. Thus the cooler air over the Southern States, as developed by the eclipse, produced a slight flow toward the Gulf of Mexico and to the Atlantic Ocean.

THE WIND AZIMUTH.

This quantity is given in Table 8 and Chart 11. The directions in azimuth are noted in the system adopted in the Cloud Report, page 138, where 0° azimuth is south, 90° east, 180° north, 270° west, and the direction is that *toward* which the wind is blowing. Thus a wind from the several quarters is given by the following azimuths:

From the N. is given by 0° azimuth.
" " W. " " 90° "
" " S. " " 180° "
" " E. " " 270° "

Chart 11 shows that the variations in the azimuth were on the average very small during the eclipse, and the means seem to indicate that there was no definite change in the azimuth or direction of the wind which could be attributed to the eclipse. There is no sufficient indication of a real gyration which would require a change in azimuth on one side of the mean before the totality, and on the other side after the totality, in order to justify pursuing this subject further and drawing conclusions in that connection. This circumstance, together with the facts that the variation of the velocity is very slight and the change in the barometric pressure minute, seems to exclude the possibility that any sort of a true cyclonic circulation was generated by the action of the cooling effect of the moon's shadow on the atmosphere.

AMOUNT OF CLOUDINESS.

The cloudiness at several stations is given in Table 9, and the mean values indicate that a slight increase took place during the hour preceding totality, and that there was a relative clearing of the air during the hour following the totality. The range is about 0.3 on a scale of 10. There was no cloudiness observed at many of the stations, so that it was not possible to continue the same system of construction in groups as before.

GENERAL REMARKS.

Looking at the meteorological effects broadly, it is safe to conclude that there was a lowering of temperature by about 3° or 4° F., a lowering of the vapor tension by about 0.007 inch, and a decrease in the wind velocity by about 1 mile per hour, caused by the eclipse shadow. There was, on the other hand, no distinct cyclonic circulation of any kind, the observed motions of the air being due simply to relative land and water changes of temperature. Mr. Clayton has drawn a very different conclusion from his observations of this eclipse, to which I took an exception in my review of his report. It should be noted that in his formula for the computation of the prevailing wind azimuth he considers $\Sigma (\sin \theta)\, v$ equivalent to $\Sigma (v.\ \sin \theta)$, as shown by his example in Science, May 10, 1901. I was misled by his unusual notation into a misunderstanding of the computation. The latter was no doubt correct. Mr. Clayton's composite of his observations of the eclipse (Ann. Harv. Coll. Obsy., Vol. XLIII, Part 1, Pl. II, fig. 5) shows that he obtained an anticyclonic circulation of very large area at the center, bounded by a low pressure belt, and a feeble cyclonic circulation extending to a high pressure area on the outside of the edge of the moon's penumbra. Compare his pressure curves of Plate III. He seems to consider this an example of a cold center cyclone, and appeals to Ferrel's old conception of the circulation of the atmosphere over a hemisphere of the earth as an analogue to it. No attempt is made, however, to quantitatively justify this comparison of the eclipse circulation with that of the hemisphere, as should be done to render the illustration valid. For in the eclipse the difference of temperature is not more than 4° F., and the force of the wind is certainly less than 2 miles per hour; in the general cyclone there is a difference of temperature of about 80° F. on the average, and by Ferrel's theory of the conservation of areas the velocity of the wind near the poles should be enormously great. At any rate the entire energy of the solar radiation is engaged in maintaining a circulation of very great power and persistency over the earth. But even in the case of the northern hemisphere, the central anticyclonic movement is actually very feeble, and even nonexistent during at least half of the year, according to our modern observations.

There are only indecisive traces of a westward circulation near the pole during certain months. If the whole dynamic action of the hemisphere can produce merely temporary indications of an anticyclonic action within 20° of the pole, that is, extending to one-fourth the distance to boundary of the circulation, can it reasonably be admitted that the feeble variations observed in the eclipse will generate an anticyclonic circulation extending halfway to the outer limits of the total movement? For the coefficient of friction is approximately $k=0.00012$, and if $v=2$ miles per hour or 0.9 meter per second, then the contribution of surface friction to the dynamic equation is 0.00011, which can properly be neglected. The great disproportion between his central anticyclonic and the outer portions makes of the dynamic circulation an unbalanced machine that will not run without going to pieces.

Mr. Clayton reproduces in Science, May 10, 1901, p. 748, fig. 4, in the central zone a northeastward wind, but in all cold cyclonic movements the wind is outward at the surface from the pole to the boundary. Ferrel describes the wind of the central zone as composed of two components of which the primary is outward. There is a feeble current of air which he supposes to be squeezed out from under the high-pressure belt in opposite directions, and decreases the primary in the central zone, but increases it in the outer, that is in the one corresponding to the trade winds of the Tropics. Ferrel assumed that the secondary component keeps to the ground and that the primary overflows it at moderate altitudes (Amer. Journ. Sci., May, 1861; Recent Advances, p. 219, 1885), but since the publication of Oberbeck's papers it has been seen that these components *merge into each other and produce a single resultant*, so that Ferrel's figure has been abandoned. Compare Sprung's meteorology, Abbe's translations, Bigelow's International Cloud Report, where these components of the general circulation are discussed. Aside from this, our recent observations, so far from confirming Ferrel's old view, show that in the lower strata it must be greatly modified in order to match the actual circulation of the atmosphere. Finally, no true cyclone, including the anticyclone which surrounds it, can have the high-pressure belt near the outer periphery, as is indicated by Mr. Clayton; the high-pressure belt is theoretically located at seven-tenths of the distance from the center in warm cyclones and still nearer to it in cold cyclones. His analogue of the cold cyclone of the hemisphere to the eclipse circulation, therefore, can not be correct.

Besides the facts that our observations do not give any indication of a true cold center cyclonic circulation, and that Mr. Clayton's result ascribes to the theoretically subordinate and usually unobserved polar component an undue influence, there is yet a more serious objection to his interpretation of his own data. Mr. Clayton assumes that the cold center circulation over a hemisphere of the earth is a true analogue to Ferrel's cold center local cyclone, such as is supposed to be formed by the chilling effect of the moon's shadow in the earth's atmosphere, but he does not show that the boundary conditions are the same in each for the generation of that type of vortex motion. On the contrary, he states that the cyclonic circulation is propagated very rapidly, 2,000 miles per hour, through the atmosphere with the motion of the shadow. But, even though the air were chilled to a degree sufficient to generate a cold-center cyclone, *it could not produce such a circulation unless the same mass of air is constantly involved.* The hemisphere does possess such a confined mass of air, but Ferrel omitted to show that the local mass of air in nature, whether having a warm or a cold center, was thus bounded by an inclosing surface of any kind, as he assumed in his theoretical treatment of the problem. It is necessary that the same mass of air should be involved, as where in laboratory experiments the water in a cylindrical vessel is heated or cooled at the center. In this case the Ferrel cyclone is developed. It was Ferrel's fatal error in constructing his theory of local cyclones that he did not show the existence in nature of such an outer bounding surface to a mass of air in gyration. To omit it and assume that the gyration would still continue of the same type is like pretending that a locomotive will work with the ends removed from the piston cylinders. The vortex type changes with the boundaries. The international cloud observations prove that the local warm-center cyclone involves fresh masses of air continuously; Clayton's eclipse cold-center cyclone does the same thing; therefore the cold-center cyclone of the earth's hemisphere is not an analogue to either of these local cyclones. Meteorologists have been neglectful of this fundamental consideration in discussing cyclonic theories, namely, that the general and the local cyclones can not be analogues of each other unless it is shown that the mass of air once involved in the circulation remains identical throughout the duration of the movement. Hence, Mr. CLAYTON's endeavor to establish such an analogue between the general cyclone and the eclipse cyclone is in reality fatal to his own hypothesis that the transit of the moon's shadow through the atmosphere can produce such a cold-center cyclone as he claims to have discovered. His further deductions regarding the diurnal barometric wave are of course involved in this untenable supposition.

It is only necessary to add a single remark regarding the relations of the local cold-center and the warm-center cyclones. These cyclones have each the same direction of rotation in horizontal planes about the vertical axis, but they differ from one another in that the vertical circulation is in opposite directions. They conform to strict mechanical principles involving closed circuits for the stream lines, and the continuous flow of the same mass of liquid. The anticyclone is, on the other hand, the product of the interference of two independent currents of air and it rotates in the opposite direction to that of the cyclone. It does not contain a system of closed circuits in itself. That is to say, having a mass of liquid in a cylindrical vessel, it is not possible by heating or cooling the central portions to generate an anticyclone. Hence the eclipse shadow could not by chilling the air in a cylindrical tube make so large an anticyclonic circulation near the center as Mr. CLAYTON has indicated. A feeble modification of the normal pressure in a cold-center cyclone might be produced near the axis when there is a large velocity of rotation and much friction. I do not here renew the question as to what extent the FERREL local cold or warm center cyclones really exist at any time in the circulation of the atmosphere, for I have elsewhere stated that it seems to be merely an ideal circulation, having little application in practice, except to some extent in the tropical hurricanes. It is perhaps unfortunate that so well-conducted eclipse meteorological observations as those of May 28, 1900, when the air was quiescent, so far as local cyclonic circulations are concerned, should yet have failed to show distinctly an appreciable change in the barometric pressure. For under the given circumstances the uncertainty of eliminating the diurnal and the cyclonic pressures from the eclipse pressure was at a minimum. The result, of course, throws great doubt upon the records of other eclipses which are supposed to have given pressure disturbances worthy of consideration At all island and seacoast stations there will occur during an eclipse a sea-breeze phenomenon, with a wind velocity in contrary directions, and an alternate change of barometric pressure. It is quite likely that this has been interpreted as an eclipse wind in some cases. The records of this eclipse for 62 stations are produced in full, with the purpose of permitting all to see how unsafe it is to draw conclusions from the indications of a few eclipse stations, as can be done by comparing the individual stations with the means of the groups or with the general means. An observer might have some local movements which it would be possible to interpret as an eclipse action, but in general the wind effect is very slight. Nor am I able from our records of the wind to detect any special change in the wind direction due to the eclipse proper. Since the velocity is a little greater before the shadow reached a given point and less after it has passed, and considering that the prevailing southwest wind, that is, a vector motion to the northeast, is feebly accelerated in front but retarded in the rear of the shadow, it is evident that this is equivalent merely to an outward flow on all sides from the entire region covered by the shadow. That is also a very natural conclusion to be drawn, judging from the entire set of circumstances. The shadow near the surface is about 4° colder than the surrounding atmosphere, and the denser air would naturally stream outward radially for a short distance. If the movement is so slight as a mile per hour relative to the undisturbed motion of the air, yet there may be produced by this means a set of ripple waves in circles surrounding the shadow. These ripple waves must have something to do with the fluttering movement observed in the shadow bands. Furthermore, the temperature disturbance in the atmosphere should be confined to the lower strata, if not to a thin stratum near the ground, because, as in the case of the diurnal range of temperature, it is only the stratum a mile or so in thickness near the surface of the earth which is notably affected by the diurnal variation of the solar radiation. It seems probable that the feeble outflow just described is something like a weak thunderstorm squall rush, and occurs very low down. The consequence of this supposition is that the ripple wave formation may be practically a surface phenomenon and may not involve the upper layers of the atmosphere, because in this region the fall of temperature due to the shadow can not be very large. The shadow cast by the earth during the night is entirely comparable to that cast by the moon during the eclipse so far as the action of the laws of radiation are concerned, and we know that the nocturnal shadow does not disturb the temperatures of the upper strata very much. This is due to two facts: (1) that the air radiates slowly as compared with the ground, and (2) that the rapid motion of the upper strata causes the process of mixture to be very effective in the higher levels. We can not expect to detect any inflow of the higher strata into the moon's shadow corresponding to the outflow at the surface, because the movement is much too feeble for any such purpose.

THE NUMBER OF CALORIES, PER KILOGRAM, ABSORBED AT THE EARTH'S SURFACE BY THE SHADOW.

The real reason for which the differential values of the pressure, temperature, and vapor tension, between the undisturbed diurnal values and the values observed during the eclipse have been obtained, was to facilitate a computation of the amount of heat cut off from the earth by the temporary presence of the moon's shadow. These data will have a bearing upon the problem of the absorption and radiation of heat by the earth's atmosphere, since the shadow of the moon during the eclipse was merely a localized space into which the heat already in the atmosphere could escape. It may be considered a restricted sort of nighttime. The use that may be made of the result depends upon the specific problem which is to be discussed. The method of computation followed is that laid down in the International Cloud Report, Weather Bureau, 1898–99, and the formula is found on page 785, the Tables 95, 96 being employed for the necessary reductions. Table 10 gives an exhibit of the work, and it begins with the data included in the

Table 10.—*Computation of the calories per kilogram of air absorbed by the moon's shadow near the ground in the total solar eclipse of May 28, 1900.*

	10 −30	11 −15	12 −5	13 Total	14 +5	15 +15	16 +30	17 +45	18 +60	19 +75	20 +90	21 +105
Normal B_n	29.76	29.78	29.79	**29.80**	29.81	29.83	29.84	29.87	29.90	29.92	29.93	29.93
Shadow B_s	29.76	29.78	29.79	29.80	29.80	29.80	29.79	29.81	29.88	29.92	29.93	29.93
T_n	72.3	72.9	73.3	**73.5**	73.7	74.2	74.8	75.5	76.2	76.8	77.4	7.81
T_s	72.3	72.0	71.4	71.3	71.3	71.1	71.4	72.2	73.6	75.4	76.8	7.81
e_n	.576	.580	.577	**.576**	.575	.577	.580	.581	.585	.581	.577	.577
e_s	.576	.578	.573	.571	.569	.570	.573	.575	.582	.581	.577	.577
THE DIURNAL ELEMENTS.												
B_n	755.91	756.41	756.67	756.92	757.18	757.68	757.94	758.70	759.46	759.97	760.22	760.22
t_n	22.39	22.72	22.94	23.06	23.17	23.44	23.78	24.17	24.56	24.89	25.22	25.61
e_n	14.63	14.73	14.66	14.63	14.61	14.66	14.73	14.76	14.86	14.76	14.66	14.66
$\frac{e}{B}$	.00193	.00195	.00194	.00193	.00193	.00193	.00194	.00195	.00196	.00194	.00193	.00193
Ia	1.35215	1.35242	1.35259	1.35269	1.35277	1.35298	1.35326	1.35359	1.35391	1.35415	1.35441	1.35473
IIa	.45486	.45491	.45493	.45495	.45498	.45502	.45504	.45511	.45518	.45523	.45543	.45543
A=Ia−IIa	.89729	.89751	.89766	.89774	.89779	.89796	.89822	.89848	.89873	.89892	.89898	.89930
THE SHADOW ELEMENTS.												
B_s	755.99	756.41	756.67	756.92	756.92	756.92	756.67	757.18	758.95	759.97	760.22	760.22
t_s	22.31	22.22	21.89	21.83	21.83	21.72	21.89	22.33	23.11	24.11	24.89	25.61
e_s	14.63	14.68	14.55	14.50	14.45	14.48	14.55	14.61	14.78	14.76	14.66	14.66
$\frac{e}{B}$	.00193	.00194	.00192	.00192	.00191	.00191	.00192	.00193	.00195	.00194	.00193	.00193
Ia	1.35215	1.35203	1.35173	1.35169	1.35168	1.35160	1.35174	1.35210	1.35275	1.35358	1.35324	1.35473
IIa	.45486	.45491	.45493	.45495	.45495	.45495	.45493	.45498	.45514	.45523	.45543	.45543
B=Ia−IIa	.89729	.89712	.89680	.89674	.89673	.89665	.89681	.89712	.89761	.89835	.89781	.89930
$B-A$	.00000	−.00039	−.00086	−.00100	−.00116	−.00131	−.00141	−.00136	−.00112	−.00057	−.00017	.00000
$273+\frac{t_n+t_s}{2}$	295.4	295.5	295.4	295.4	295.5	295.6	295.8	296.3	295.8	296.5	298.1	298.6
Calories	0.000	0.115	0.254	0.295	0.343	0.387	0.416	0.403	0.331	0.169	0.051	0.000

columns 10 to 21 of the preceding compilation of the observations taken during the eclipse. The arguments are placed at the side of the table, and now the actual values of the elements as determined for the normal curves and the shadow curve can be constructed from the curves. These are entered in Table 10, $B_n \,.\, t_n \,.\, e_n$. for the undisturbed diurnal curve of May 28, 1900, and as $B_s \,.\, t_s \,.\, e_s$. for the shadow curve of that date. They are scaled from the curves and are entered in English measures. In the case of the pressure the shadow curve shows a general drop on the other groups, which is not an eclipse effect, and it is included, as the influence on the computation is very slight. The differences $B_n - B_s$, $t_n - t_s$, $e_n - e_s$ are the same as the shadow variations found at the end of the respective tables of the three elements, so that the data are in harmony with the preceding discussion. These data are now transformed into metric measures, and the diurnal elements and the shadow elements are collected in separate groups. The ratio $\frac{e}{B}$ is computed for the several sets. The formula for the computation of the calories per kilogram required to transform a kilogram of air under certain conditions ($B_n \,.\, t_n \,.\, e_n$.) into another condition ($B_s \,.\, t_s \,.\, e_s$.) is as follows:

$$\int \frac{dQ}{T} = (\lambda c_p + \mu c'_p) \log \frac{T}{T_o} - A(\lambda R + \mu R_1) \quad \log \frac{p}{p_o}, \qquad \text{or, in another form,}$$

$$\int dQ = Q = T\left[\left(.2374 + .1512\frac{e}{B} + .0232\frac{e^2}{B^2}\right) \log T - \left(.06858 + .02592\frac{e}{B}\right) \log B\right]_n$$
$$- T\left[\left(.2374 + .1512\frac{e}{B} + .0232\frac{e^2}{B^2}\right) \log T - \left(.06858 + .02592\frac{e}{B}\right) \log B\right]_s,$$

where the first line refers to the diurnal and the second to the shadow elements. The first terms in each line are the same as I_a in Table 65, and the second the same as II_a in Table 66. It is not necessary to go beyond this point in the discussion, because the elements remain throughout in the unsaturated α stage. Since the range in the temperature is small—that is, less than 4° F., it is proper to take the mean temperature $t = \frac{t_n + t_s}{2}$ for the several sets to be computed. With the arguments $\left(t, \frac{e}{B}\right)$ take out I_a, and with $\left(B, \frac{e}{B}\right)$ take out II_a. Subtract the values for A and B in the diurnal and the shadow respectively. Since A is the undisturbed value and B the value which occurs in consequence of the transit of the shadow, the difference, $B - A$, is the loss of heat caused by the radiation into the shadow during its presence at a given station, and it is the mean or the representative of the entire system of observations. Multiply the values $(B - A)$ by T, as computed for each set, and we obtain the number of calories of heat absorbed by each kilogram of air. Since a kilogram is equivalent to about seven-tenths of a cubic meter of air at the earth's surface, these are the amounts absorbed by this volume. Hence, one can compute, if desired, the total amount absorbed by the shadow, in a layer one meter thick, and throughout the entire cone as limited by any assigned upper layer, provided the proper variation of the absorption with the elevation is known. Such an extension of the problem involves several quantities which are not now available.

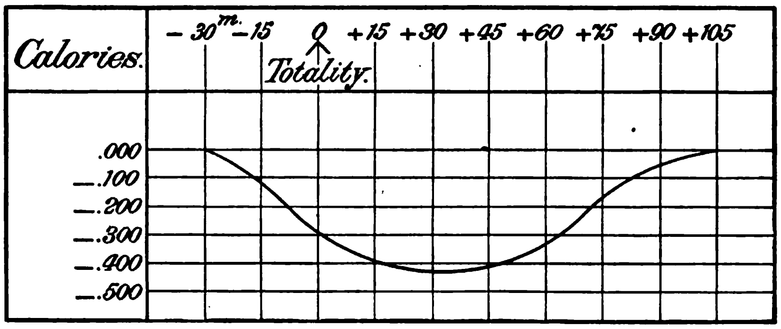


CHART 12.—The number of calories per kilogram absorbed by the moon's shadow May 28, 1900.

Chart 12 gives a graphic representation of the result of the computation, and it shows that beginning with column 10, 30 minutes before totality, the number of calories absorbed increased to 4.40 at 15 minutes after totality, and then decreased to zero at about 93 minutes after the totality. From 15 minutes after totality to 45 minutes after totality there was very little change, and I regard 30 minutes after totality as the moment of the true maximum. This divides the curve into two nearly equal parts, and gives 45 minutes for the absorption of the heat and about 45 minutes for the return to a normal diurnal condition of the atmosphere. The amount of heat required to transform the shadow kilogram into the diurnal kilogram is about half that required to transform an adiabatic kilogram into the same diurnal kilogram. I think that the gradual collection of such data as the foregoing will throw valuable light upon the problem of atmospheric absorption and radiation, and that in future eclipses efforts should be made to conduct the meteorological observations on as large a scale as is practicable, instead of confining them exclusively to the eclipse stations.

CHAPTER 3.

THE OBSERVATIONS ON THE SHADOW BANDS AND DISCUSSION OF THE RESULTS.

THE INSTRUCTIONS FOR THE OBSERVATION OF THE SHADOW BANDS.

In order to secure observations on the phenomenon of the shadow bands, which are seen just before the total eclipse occurs and also just after the shadow passes an observer stationed in the path of the totality, a suitable set of instructions for conducting the work was issued by the Weather Bureau. This form was distributed to many persons located in the shadow path, who volunteered to make the necessary preparations and record the results, and replies were received from 40 or 50 persons, either giving some data or else stating that they were unable to secure the observations. The following report is based upon the work of 34 observers who have contributed important facts bearing upon the phenomenon in question. A copy of the instructions and the form for recording the results is added in order to show exactly what it was that the observers attempted to perform.

METEOROLOGICAL OBSERVATIONS DURING THE TOTAL ECLIPSE OF THE SUN MAY 28, 1900.

U. S. Department of Agriculture, Weather Bureau,
Washington, D. C., May 15, 1900.

By direction of the Chief of the Weather Bureau, the following special meteorological observations will be taken during the hours of the eclipse of the sun, May 28, 1900, at the stations receiving this order:

It is particularly important to set the clocks and sheets of all the self-registering apparatus as accurately as possible before the time of the eclipse, and have the pens in perfect working order.

The inclosed form for the original records is practically the same as Form No. 1001–Met'l, and the observations are to be made precisely as usual, but with all possible care to avoid personal equation in the readings, at the minutes of seventy-fifth meridian time indicated on the margin. The correction for elevation need not be applied at the station, and the column marked "Ratio $\frac{e}{B}$," will be left blank. In case it is not convenient to make all these observations very near the minute indicated, then the observers should subdivide the work so that each set shall be practically simultaneous at the appointed time. The wind direction and velocity, also the direction and motion of all kinds of clouds visible, are required as carefully as possible. Under remarks on the state of the weather note clearly all circumstances attending the progress of the eclipse, but the space on the form may be used simply to make references to more extended notes, which will be filed with this report.

The observations will probably indicate a fall in temperature and increase in relative humidity; a backing of the wind for a time followed by a veering; possibly a small change in the pressure, if it can be distinguished from the diurnal range and from the local cyclonic movements. It is desirable that these observations be continued hourly till the 8 p. m. regular observation, but they are voluntary beyond the times specified on the forms.

THE SHADOW BANDS.

The observations on the shadow bands are voluntary at all the Weather Bureau stations, but it is hoped that the method of observing them may be explained to persons who will cooperate with the Weather Bureau officials by undertaking them. Such work on the bands should be carried on at as many places as possible throughout the region covered by the track of totality, but they are more valuable along the edges than on the central line.

Just before and just following the instants of totality—that is, the second and third contacts—a series of shadow bands pass over the ground, in different directions at the two contacts. It is very important to observe the following points regarding them: (1) The direction of motion, which is that perpendicular to the bands themselves; (2) the velocity of motion; (3) the number of bands and light spaces per yard; (4) the study of flickering characteristics and other physical aspects that they may present. It is necessary to make these observations as follows: Smooth a piece of ground carefully and fasten a large white sheet without wrinkles so that the edges shall be oriented exactly N. to S. and E. to W.; lay down a straight stick 2 yards long parallel to the bands at the first appearance of them before the totality and leave it in place, and then another stick when they appear again after totality; measure the exact angle between these sticks, and between each of them and the true north and south line; provide a board 2 yards long painted black and white in alternate feet, making three black spaces and three white spaces, and lay it down in the direction the bands are running; count the number of bands seen on the whole or a portion of this board as is convenient and easy to do with accuracy, and thus estimate the width of the bands and of the light spaces, respectively; run alongside the bands at an equal pace with their motion and determine by comparison with a measured distance the velocity in the number of feet per second. Note any peculiarities of the bands actually seen and not imagined. It will probably be possible to secure the assistance of others, so that the several parts of this work may be assigned to different persons, and confusion should be avoided by sufficient preliminary practice. Much will depend upon the good judgment of the observers. These eclipse bands are to be seen most favorably near the edges of the shadow of the totality, and it is much to be hoped that persons who happen to be in such places may be induced to cooperate in this special observation. Your knowledge of the locality may enable you, by your correspondence, to secure the services of several such parties.

All the records should be mailed to the central office exactly as originally made and without modification when once the figures are entered. Supposed mistakes may be referred to by means of side notes and special remarks.

WEATHER BUREAU OFFICES HAVING ONLY ONE REGULAR OBSERVER.

Whenever there is only one observer at a station all the observations here indicated which will interfere with the necessary duties of the station, such as the taking of the morning observation, the preparation of the map, the distribution of the forecasts, etc., will be omitted, but all the data which can be acquired outside this limitation should be entered and transmitted. In these stations reliance must be placed on the self-registering apparatus, but it is always preferable to read the standard instruments.

Respectfully,

Frank H. Bigelow,
In Charge of the Eclipse Observations.

For Volunteer Observers.

[Form for observing the shadow bands of the total eclipse of the sun May 28, 1900.]

Watch carefully for the time when the first thin crescent is disappearing for the beginning of the bands; the bands may be expected three minutes earlier.

BEFORE THE TOTALITY.

1. Note time (local or 75th meridian) of beginning: Hour minute second . Corrected time should be entered in all cases.
2. Direction of bands parallel to the first stick: Degrees minutes from N. to S. line; recorded north with degrees east or west.
3. Number of bands in a yard: bands; light spaces.
4. Relative width of the bands and spaces: The bands were as the spaces.
5. Velocity of motion of the bands by pacing: The bands moved feet per second.
6. Note time when the bands disappeared: Hour minute second

AFTER THE TOTALITY.

7. Note time (local or 75th meridian) of beginning: Hour minute second .
8. Direction of bands parallel to the second stick: Degrees minutes from N. to S. line.
9. Number of bands in a yard: bands; light spaces.
10. Relative width of the bands and spaces: The bands were as the spaces.
11. Velocity of motion of the bands by pacing: The bands moved feet per second.
12. Note time when the bands disappeared: Hour minute second .

It should be noted that the form itself required simply the direction in which the bands themselves lay, as referred to a north and south line, and this was done in order to avoid confusion of the direction of the bands with the direction of the motion, which was usually at right angles to the bands. After the replies had been examined, a letter of inquiry was addressed to the several observers requesting further information regarding the direction of the motion as an independent fact. The letters in return contained interesting and important remarks on the appearance of the bands, some of which have been reproduced for further examination in studying the theory of the cause of the shadows themselves. Extracts from the reports are incorporated at this place for the guidance of the reader.

NOTES ON THE DIRECTION OF MOTION AND THE APPEARANCE OF THE SHADOW BANDS.

Virginia Beach, Va.—Some little difficulty was experienced in determining in just what direction the bands were moving; that is to say, whether southwest or northeast. My impression of the bands was that there was more than one set and that they may have been moving in diametrically opposite directions. The effect was very like that of walking parallel to a double line of picket fence and observing the flicker and apparent contrary movement caused by the shifting of the relative positions of the lights and open spaces. In addition to this flicker of the bands there seemed to be a regular transverse sliding of the bands, which gave the effect that a third set of bands would give if superimposed upon the others and made invisible in some way in the light spaces. It has seemed probable to me that there may have been a considerable number of sets of bands, but the illumination being from practically a slit (a crescent of only a few degrees in arc), only those that lay parallel to it would be clearly defined.—Greenleaf W. Pickard.

Monticello, Ga.—The bands or shadows were not continuous, but veering, undulating, and flickering. The motions of the bands were flickering, zigzag, and partly indistinct, moving rapidly. It was impossible to measure their velocity.—C. H. Jordan.

Lancaster, S. C.—The shadow bands were moving northeast before and southwest after totality, not exactly in an inverse direction, but more south of west and north of east.—T. H. Davis.

Three miles east of Lancaster, S. C.—At their second appearance the bands were moving in the same direction—viz, toward northeast—as at the first appearance. Near the time of second contact there was a mingling of light and dark upon the sheet a few seconds before the bands themselves appeared. The bands were wavy and irregular in character and were too dim to be seen on the board divided into foot spaces. Mr. Culp describes the bands as irregularly and finely chopped up shadows moving over the sheet at about the speed of the flickerings noticed in a "cinematograph" or "vitascope" picture when poorly projected on a screen. Miss Cook describes the bands as parallel, wavy, dark bands about an inch wide. She insists that about two minutes after the second set of bands disappeared she noticed a third set of bands upon the sheet extending parallel with its longer edge—that is, N. 18° W. magnetic and moving westward.—Cleveland Abbe, Jr.

Longshore, S. C.—The shadow bands moved to the northeast before totality; also in the same direction after totality. The strangest thing about the eclipse was the flashes of light playing on my sheet just after the shadow bands commenced and before they ceased to move. It had the appearance of a flash made by the sun on a small round looking-glass and had the shape of a small horseshoe. It played over the sheet rapidly just before the bands commenced to move and then just as they ceased after totality.—W. G. Peterson.

Polkton, N. C.—Before totality the bands moved from southwest toward northeast; after totality they were very indistinct, but seemed to move from nearly southeast toward northwest. The bands were very obscure and hard to see on a white sheet. At places 8 or 10 miles away they were very apparent anywhere on the earth's surface. They traveled rapidly, seemingly as fast as a bird flies.—W. F. Humbert.

Morgan City, La.—We could not get the velocity of the bands nor the number of the bands per yard. The bands quivered to the extent of dazzling the eyes.—B. M. Young.

Spring Hope, N. C.—The bands moved in the same direction—that is, northeast—before and after totality. The bands were not straight, but curved almost crescent shape.—George W. Bunn.

Raleigh, N. C.—Just before totality the bands seemed to me to consist of narrow pencils of light and shadow extending directly from west to east and appearing to move directly from west to east in the direction of their length. After the totality the bands were so faint that the direction in which they lay and their movements could not be determined. I received the impression that they lay from northwest to southeast, but moved from west to east.—C. F. von Herrmann.

Raleigh, N. C.—The bands flickered and moved so that it was rather difficult to estimate their number and velocity of motion.—B. Irby.

Auburn, Ala.—No shadow bands were seen, or, if so, it might be imaginary. I had five men to assist me and none of them saw anything.—Troy Pool.

Auburn, Ala.—The bands were indistinct, flickering, and apparently darkest at the rear edge, shading out gradually to the light band next in front. In their movement they gave the sheet the appearance of being in motion similar to that produced by a strong current of air blowing under it, or like it was being shaken rapidly from one side. This condition was so marked as to deceive persons standing about, and one gentleman remarked that the strong breeze which sprung up about the time of totality had gotten under our sheet. On the second appearance of the bands it was observed that they changed direction of motion. When they first started they were moving almost due east, but at the end of their appearance they had changed through an angle of about 13° to the north. We have no definite observation to indicate that the first set changed direction, but I have an impression that they did change slightly from a little west of north to a little east of north.—JOHN J. WILMORE.

Santuck, S. C.—The bands were very dim, looking like thin smoke passing over the sheet, and we could not distinguish well enough between the bands and light spaces, but estimate the bands were about 2 inches wide. I noted the peculiar look and shape of the shadows of tree leaves before the totality, which were crescent shape and as if in two lights, sending rays across each other. Before totality the bands were moving slightly to the west of north. After totality they moved toward east by south.—E. W. JETER.

Louisburg, N. C.—Before totality the bands were very nearly due east and west, the line of motion being to the north. (It may be that it was very slightly toward the east, but, as said above, the bands were nearly due east and west.) Afterwards they were at right angles with the first, and the line of motion was toward the east. There was an appreciable fall of temperature and a deposit of dew; a peculiar yellow appearance of everything, and the shadows were unusually shaped. I was told by a party who saw the bands at Youngsville that they were north and south just before totality. He was somewhat frightened, according to his version, by the dust moving on the ground although there was no wind. I take it that the dust mentioned was the shadow bands.—THOMAS B. WILDER.

Albemarle, N. C.—The shadow bands moved to the northeast before totality and to the southwest after totality. They began to flicker across the ground just before the second contact, coming from the direction indicated, and changed rapidly around by the west to the northeast without stopping. They were indistinct, flickering, about 1 to 2 inches wide, and were traveling at a rapid rate.—G. M. DRY.

Elberton, Ga.—The shadow bands passed over in one direction N. 30° W. before totality and in the opposite direction immediately after totality.—H. A. ROEBUCK.

Senoia, Ga.—The first bands pointed east and west and moved north; after totality they pointed from northwest to southeast, but moved exactly to the northeast. They were flickering and very unsteady and traveled so fast that it was impossible to pace them, nor could we tell their relative size or the number of bands in a yard.—W. R. MCCRAY.

Little Mountain, S. C.—The shadow bands were apparently only a fraction of an inch in width, with a dancing, shimmering motion, whose velocity could not be estimated. It had something of the appearance of a back-and-forth motion. The bands extended N. 50° W., according to my measurements, and were the same in direction before and after totality. The general direction of motion before totality was to the northeast. I am not sure whether or not the motion was reversed after totality, but think it was not.—L. C. GLENN.

Hobgood, N. C.—The little shadows ran over a sheet so dim and fast that I could not make any calculations.—IVEY M. PARKER.

Bay St. Louis, Miss.—I noticed the shadow bands about a minute before totality and a minute after, but their precise direction, their number per foot, and their velocity could not be ascertained on account of shortness of duration—two or three seconds each time. They appeared to move in curved lines, 1 to 2 inches thick, in a southwest direction before and in a northeast direction after totality.—BRO. ISIDORE.

Wilson, N. C.—The bands were too indistinct at first contact to admit of any calculations. At the second contact the bands were of a flickering nature, following one another at regular intervals, bearing to the light spaces the ratio of 1:4 in width.—H. H. HUTCHINSON.

Cheraw, S. C.—The first appearance of the bands before totality was very faint and indistinct and hard to discern in their motion, but I am strongly under the impression that they moved from northeast to southwest. The bands after totality were quite visible and easily discerned, and they moved from south to north. The bands moved at a very rapid rate, and the time was so short that it was not easy to see everything about their movement. They moved in a wavy and flickering manner as they appeared to the eye.—H. L. LOUGHLIN.

Biloxi, Miss.—No bands were visible before totality. The bands were observed after totality very indistinctly, running or moving from north to south, but too quick for thorough observation or measurement. They flickered badly.—J. J. LEMON.

Batesburg, S. C.—The bands ran in opposite directions—before totality northeast and after totality southeast or slightly more toward the south.—E. J. HITE.

The bands were reported to have been seen at Montgomery, Ala., at Columbia, S. C., just to the south of the line of totality, and also at Charleston, S. C., but no very definite observations were made of them at those places.

Out of these observations we may summarize the following facts on the general appearance of the bands: These had, (1) a flickering, wavy, and unsteady motion, noted generally, but specifically at Virginia Beach, Va., Monticello, Ga., Lancaster, S. C., Raleigh, N. C., Auburn, Ala., Albemarle, N. C., Little Mountain, S. C., Wilson, N. C., Cheraw, S. C.; (2) the velocity and other conditions could not be measured on account of their unsteadiness at Monticello, Ga., Polkton, N. C., Morgan City, La., Raleigh, N. C., Senoia, Ga., Little Mountain, S. C., Hobgood, N. C., Bay St. Louis, Miss., Biloxi, Miss.; (3) there was a mingling of light and shade a few seconds before the bands appeared at East Lancaster, S. C.; (4) there seemed in two cases, at

Virginia Beach, Va., and at Santuck, S. C., to be a superposition of two or even more sets of separate bands; (5) the shape of the bands was described as follows just before and just after totality: As horseshoe shaped at Longshore, S. C.; as crescent shaped at Spring Hope, N. C.; as having curved lines at Bay St. Louis, Miss.; as darkest on the rear edge at Auburn, Ala.

From all this we draw the conclusion that the shadows were crescent shaped, and had a flickering motion as if struggling through two or more conflicting movements in the atmosphere itself. It may be stated here by way of anticipating a part of the view to which we have come regarding the physical origin of the shadow bands, that there seem to be decisive arguments against the idea that they are a diffraction phenomenon in any way. On the other hand, the images of the sun, or the partial disks which are seen on the ground underneath the leafy foliage of a tree, projected through the light spaces between the leaves, seems to be a suggestive picture of the process which is involved. We have here several independent observations that the bands had a crescent shape, like the disappearing or the appearing thin crescent of the sun at the second and the third contacts, respectively. We hope to show that the edges of the umbra for a considerable distance from the theoretical geometrical edge is in reality made up of patches of shadow and patches of light, caused in part by the meteorological air currents of the upper and lower strata, and by the thrusting into the atmosphere of a distinctly colder cone, which sets up undulations and disturbances near its surface that must influence the appearance of the rays of light passing through them. The separate flickering bands may be thus referred to the independent air currents of the atmosphere, and the irregular absorption, refraction, and reflection of light on the roughly constructed edge of the umbra may be likened to the effect of the broken foliage on the sun's image, whereby a multitude of separate disks are produced on the ground beneath it. In this way the single thin crescent of the sun at the moment before totality, by passing through such a semiopaque medium which must surround the umbra, may be multiplied into numberless images, and these would also possess the wavy and flickering features so uniformed ascribed to them by many observers. Without attempting to further explain this view at this point, we will pass on to a further description on the observations, which seem to point strongly if not conclusively to this general idea.

THE OBSERVATIONS ON THE SHADOW BANDS BEFORE AND AFTER TOTALITY.

The observations on the shadow bands have been collected in two tables, 11 and 12, the first before totality and the second after totality. In these tables the stations are separated into two groups, the first containing those which are located north, and the second those which are south of the central line of the shadow path, the former having 20 and the latter 10 stations. About 50 stations or observing parties reported to the Weather Bureau, but only those included in the tables had valuable results. The first column contains the stations; the second the observer's name; the third the relative distance from the center, on the supposition that the radius of the shadow path is equal to 100; the fourth column gives the direction in which the bands were observed to lay upon the ground, and the fifth that toward which the bands as a group appeared to be moving; the sixth gives the velocity of their motion in feet per second; the seventh column contains the width of the dark bands in inches, and the eighth that of the light spaces; the ninth gives the observed time when the bands were first seen; the tenth the time when they disappeared, and the eleventh the apparent duration. The material from which these tables were constructed makes it very evident that the observers had been laboring under great difficulties in their attempts to make definite observations on the shadow bands.

TABLE 11.—*Observations made on the shadow bands at the eclipse of May 28, 1900.*

BEFORE TOTALITY.

Station	Observer	Distance center. Rad. = 100	Direction of bands	Direction of motion toward	Velocity of motion	Width of bands	Width of spaces	Begins	Ends	Duration
								75th meridian time		
NORTH			°	°	*Ft. per sec.*	*Inches*	*Inches*	*h. m. s.*	*h. m. s.*	*m. s.*
Virginia Beach, Va.	Pickard	5	N 32 W	S 43 W	8	1.5	2.5	8 50 30	8 52 46	[2 16]
Newberry, S. C.	Houzeal	10	....	....	....	....	....	....	....	....
Monticello, Ga.	Jordan	11	N 18 W	NE	....	1.0	1.0	8 40 27	8 41 43	[1 16]
Winton, N. C.	Daniel	15	N 44 W	....	Fast	1.5	1.5	8 50 26	8 50 41	0 15
Lancaster, S. C.	Davis	25	N 56 W	N 31 E	15	One-third as wide		....	8 43 0	....
	Wallace	25	N 50 W	NE	10	About as wide		8 49 0	....	....
	Wilds	25	N 41 W	NE	10	1.0	1.0	....	....	....
	Norris	25	N 30 W	E	....	....	....	8 44 10	....	....
Longshore, S. C.	Peterson	31	N 40 W	N 50 E	....	....	....	....	....	....
Polkton, N. C.	Humbert	34	....	NE	Rapid	....	....	....	....	....
Morgan City, La.	Young	38	N 86 W	....	....	1.5	1.5	8 28 27	....	....
Springhope, N. C.	Bunn	42	N 66 W	NE	2	1.5	2.0	....	....	....
Raleigh, N. C.	Von Herrmann	45	N 90 W	E	....	....	....	8 47 ..	8 49 ..	....
	Irby	45	N 76 W	....	3	1.0	1.5	8 47 42	8 48 ..	....
Auburn, Ala.	Wilmore	71	N 88 W	N 2 E	11	5.0	10.0	8 36 25	8 36 35	0 10
Candor, N. C.	Hight	73	N 49 W	....	2.5	0.5	2.5	....	8 20 15	....
Santuc, S. C.	Jeter	75	N 71 E	N 20 W	....	2.0	2.0	8 9 51	....	....
Wake Forest, N. C.	Lanneau	77	N 85 W	....	....	....	....	....	....	....
Louisburg, N. C.	Wilder	88	N 90 W	N	5	1.0	4.0	8 47 49	....	....
Rock Hill, S. C.	Culp	97	N 92 W	N	....	1.5	1.5	....	....	....
Mount Willing, Ala.	Garrett	98	N 85 W	N	4	1.0	4.0	8 37 22	8 37 30	0 8
Albemarle, N. C.	Dry	100	N 60 W	NE	Rapid	1.5	1.5	8 44 ..	....	....
Elberton, Ga.	Roebuck	100	N 60 E	N 30 W	6	3.0	3.0	8 47 ..	8 47 30	....
Senoia, Ga.	McCray	110	N 90 W	N	....	0.5	0.5	8 38 ..	8 38 30	....
SOUTH										
Rockingham, N. C.	Stansill	17	....	....	6	0.5	0.5	8 45 15	8 45 30	0 15
Little Mountain, S. C.	Glenn	25	N 50 W	NE	....	0.5	0.5	....	....	....
Hobgood, N. C.	Parker	30	NW	NE	....	....	....	8 48 ..	....	....
Bay St. Louis, Miss.	Br. Isidore	36	NW	SW	....	1.5	1.5	....	....	....
Selma, N. C.	Noble	42	N 45 W	NE	....	2.0	2.0	8 48 0	....	....
Wilson, N. C.	Hutchinson	44	N 100 W	....	....	....	....	8 44 30	8 49 30	....
Cheraw, S. C.	Loughlin	58	N 52 W	SW	7	0.5	3.0	8 45 54	8 46 0	0 6
Biloxi, Miss.	Lemon	64	....	....	....	....	....	....	....	....
Belcross, N. C.	Godfrey	80	N 5 E	....	3	1.0	1.0	8 54 10	8 54 30	0 20
Batesburg, S. C.	Hite	95	NW	NE	6	0.5	1.0	....	8 42 0	....
Means		....	....	....	6.6	1.37	2.15	....	....	12.3
Averages		....	....	....	6.45	1.30	2.20	....	....	13.3
						3.50				

TABLE 12.—*Observations made on the shadow bands at the eclipse of May 28, 1900.*

AFTER TOTALITY.

Station	Observer	Distance center Rad. = 100	Direction of bands	Direction of motion toward	Velocity of motion	Width of bands	Width of spaces	Begins	Ends	Duration
								75th meridian time		
NORTH			°	°	*Ft. per sec.*	*Inches*	*Inches*	*h. m. s.*	*h. m. s.*	*m. s.*
Virginia Beach, Va.	Pickard	5	N 42 W	S 43 W	8	1.5	2.5	8 54 21	8 56 30	[2 9]
Newberry, S. C.	Houzeal	10	N 48 W	NE	7	1.0	2.0	...	...	0 10
Monticello, Ga.	Jordan	11	N 31 W	SW	4	0.5	1.5	7 43 14	7 43 26	0 12
Winton, N. C.	Daniel	15	...	...	...	...	...	...	...	...
Lancaster, S. C.	Davis	25	N 32 W	S 20 W	...	One-third as wide		8 44 1	8 44 10	0 9
	Wallace	25	N 50 W	NE	10	Same width		...	...	...
	Wilds	25	N 41 W	NE	10	1.0	1.0	...	...	...
	Norris	25	N 30 W	E	...	...	...	...	...	...
Longshore, S. C.	Peterson	31	N 40 W	N 50 E	...	...	...	...	...	...
Polkton, N. C.	Humbert	34	...	NW	...	...	...	...	...	...
Morgan City, La.	Young	38	N 26 W	...	...	1.5	1.5	8 30 24	...	...
Spring Hope, N. C.	Bunn	42	N 61 W	NE	2	2.0	3.0	...	...	...
Raleigh, N. C.	Von Herrmann	45	N 45 W	E	...	...	...	...	...	...
	Irby	45	N 43 W	...	3	0.7	1.5	8 49 42	8 50 57	[1 15]
Auburn, Ala.	Wilmore	71	N 13 W	N 77 E	11	4.0	8.0	8 37 55	8 38 5	0 10
Candor, N. C.	Hight	73	N 40 E	...	2.5	0.5	2.5	8 24 15	8 25 10	0 55
Santuc, S. C.	Jeter	75	N 11 E	N 100 E	...	...	...	8 10 48	...	...
Wake Forest, N. C.	Lanneau	77	N 32 W	...	...	...	...	...	...	...
Louisburg, N. C.	Wilder	88	N 0 W	E	...	...	...	...	8 51 10	...
Rock Hill, S. C.	Culp	97	N 36 E	NW	...	1.5	1.5	...	...	...
Mount Willing, Ala.	Garrett	98	N 11 E	E by S	5	1.0	3.0	8 38 27	8 38 34	0 7
Albemarle, N. C.	Dry	100	N 40 E	SW	Rapid	1.5	1.5	...	...	...
Elberton, Ga.	Roebuck	100	N 60 E	S 30 E	6	3.0	4.0	8 47 40	8 47 45	0 5
Senoia, Ga.	McCray	110	N 45 W	NE	...	...	...	...	...	...
SOUTH										
Rockingham, N. C.	Stansill	17	...	...	6	0.5	0.5	8 46 15	8 46 30	0 15
Little Mountain, S. C.	Glenn	25	N 50 W	NE	...	0.5	0.5	...	...	...
Hobgood, N. C.	Parker	30	...	...	...	...	...	...	...	...
Bay St. Louis, Miss.	Br. Isidore	36	...	NE	...	1.5	1.5	...	...	...
Selma, N. C.	Noble	42	N 65 W	NE	...	...	...	8 49 30	...	...
Wilson, N. C.	Hutchinson	44	N 80 W	...	10	1.0	4.0	8 50 25	8 50 27	0 2
Cheraw, S. C.	Loughlin	58	N 86 W	...	7	0.5	3.0	8 46 0	8 46 8	0 8
Biloxi, Miss.	Lemon	64	...	S	...	0.3	2.0	...	...	0 15
Belcross, N. C.	Godfrey	80	N 5 E	...	3	1.0	1.0	8 56 10	8 56 35	0 25
Batesburg, S. C.	Hite	95	NE	SE	6	0.5	1.0	...	...	...
Means		...	...	...	6.3	1.21	2.24	...	...	14.4

During this eclipse in the United States the shadow bands had a very indistinct appearance, much less prominent and marked than that which they have been described to possess at several other eclipses. The duration was very short, the bands and spaces small and flickering, and there was evidently much uncertainty in assigning to them the direction of motion, whether to the northeast or to the southwest. Before totality 18 observers gave a direction of northeast, and 3 of southwest; after totality 16 made it northeast, and 7 made it southwest. We may conclude that the motion was in reality about northeast before and after the totality, and that the uncertainty arose from the deception which the shimmering light exerted upon the observers. A similar case occurs when there is a motion of two sets of bars making an angle with each other, but wherein the bars in each set are parallel to one another. If these groups are moved by each other, it is not always easy to assign the direction of the apparent motion of the resultant optical effect.

It will be seen by an examination of the weather maps of May 27 and 28 that an area of high pressure was central over the South Atlantic and East Gulf States, which produced generally fair and clear weather in the eclipse districts. To the northward, in the Ohio Valley and New England, there was a rainy condition, though the pressure was comparatively high in all districts east of the Mississippi River. These conditions favored a very quiet state of the atmosphere in the Atlantic and Gulf States, with steady vertical gradients for the pressure, temperature, and vapor tension. I presume that this was the chief cause why the bands appeared to be small, and that if the circulation of the atmosphere had been more vigorous and congested the bands would have been larger—as much as 6 or 8 inches in breadth—such as have been observed on other occasions. This quiescent state of the air favored the formation of small bands, on the supposition that they are in part at least to be referred to the wavy and undulating currents moving in the upper strata. If these are of small dimensions the effect will be small waves, but if they are large then the bands will come down wider. When the full sun shines through these upper wavy strata its light is so powerful as to overcome any small variations that these waves could produce by the absorption or irregular refraction; but when the light is reduced to a thin crescent, then local atmospheric absorption may be of distinct importance in determining the amount that is finally received at the earth's surface. Furthermore, under the circumstances existing on May 28, it is inferred that two principal air currents were moving over the Gulf States, since the lower strata were moving northward, as controlled by the anticyclonic pressure, and the upper strata directly eastward, under the influence of the undisturbed circulation of the general atmosphere such as is described in the International Cloud Report of 1899. These two currents, making an angle of about 90 degrees with each other, would suggest that two principal sets of waves or ripples must have existed in the atmosphere, of small dimensions in general, but so disposed as to cause the effect of a shimmering and unsteady motion upon the rays of light which were observed through this medium.

DIAGRAMS OF THE DIRECTION OF THE SHADOW BANDS AND THE DIRECTION OF MOTION.

In order to exhibit more distinctly the facts contained in the fourth and fifth columns of Tables 11 and 12, regarding the direction of the shadow bands and their motion before and after totality, these data have been transferred to Charts 13 and 14. The outer circle of Chart 13 represents the section of the umbra which passed over the Gulf and South Atlantic States, and which was about 50 miles in diameter. The double line separates the diagram into two parts at right angles to the line that represents the direction of the motion of the shadow, which itself makes an angle of about 60° with the north and south line. The preceding portion of the diagram is devoted to the data for the bands before totality, and the following to those after totality. The relative distance of the several stations at right angles to the path was measured approximately on a large map, and each station was located on the circle at the appropriate place both before and after the totality. The duration, being determined by the length of the chord and its distance from the central diameter, is indicated by the position of the station. The position of the bars and the arrows shows the observed places of the shadow bands and their direction of motion, respectively. The same remarks apply to Chart 14, which merely locates the bands geographically, instead of collecting them as if seen simultaneously at one time.

The following remarks seem to be justified by the aspect of these charts. A large majority of the stations agree in assigning one direction to the general motion, namely, northeastward, instead of two directions, that is opposite after totality to that before the totality. The apparent opposite motions reported by several observers must have been due to an error of judgment caused by the shimmering motion of the bands. This general direction is found to be N. 42° E. before and N. 59° E. after totality, when the directions are all corrected to read northeastward. There is a difference of 17° between these two directions. The bands themselves lay generally in a northwesterly direction, and taking the directions exactly as they stand in the table the mean direction is N. 50° W. before and N. 22° W. after the totality. The difference is 28° and the direction of azimuth rotation is the same, that is eastward, as in the variation of the mean directions. Allowing more weight to the result for the direction of the bands than to that for the direction of motion, because more specific attention was paid during the eclipse to that special observation, we may conclude that the bands and the motion veered about 20° or 25° from the time before to the time after totality.

The direction of the shadow bands, and the direction of motion, before and after totality, as if observed simultaneously.

CHART 13.

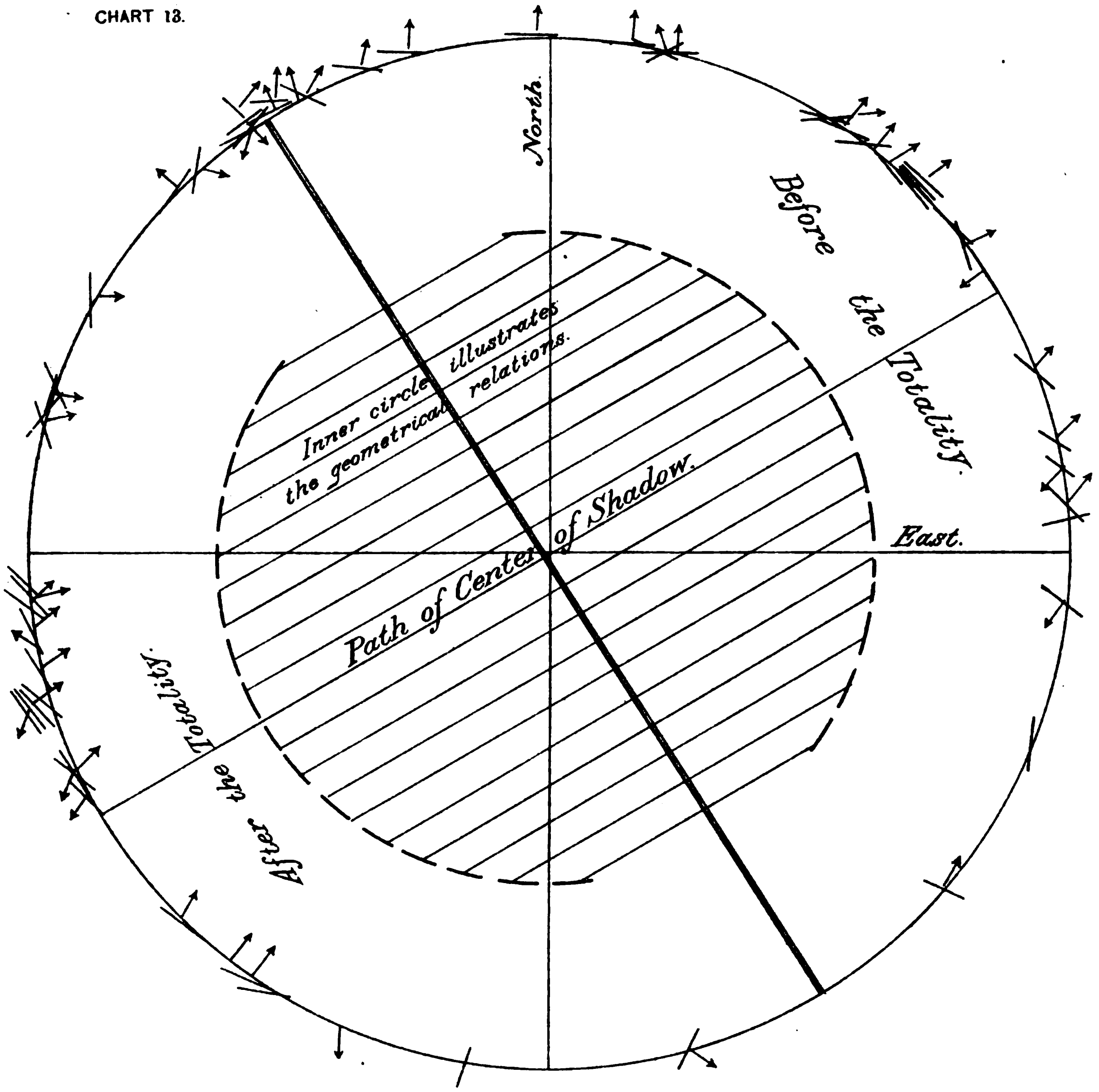

North.
East.
Before the Totality.
After the Totality.
Inner circle illustrates the geometrical relations.
Path of Center of Shadow.

CHART 14.

The same plotted geographically.

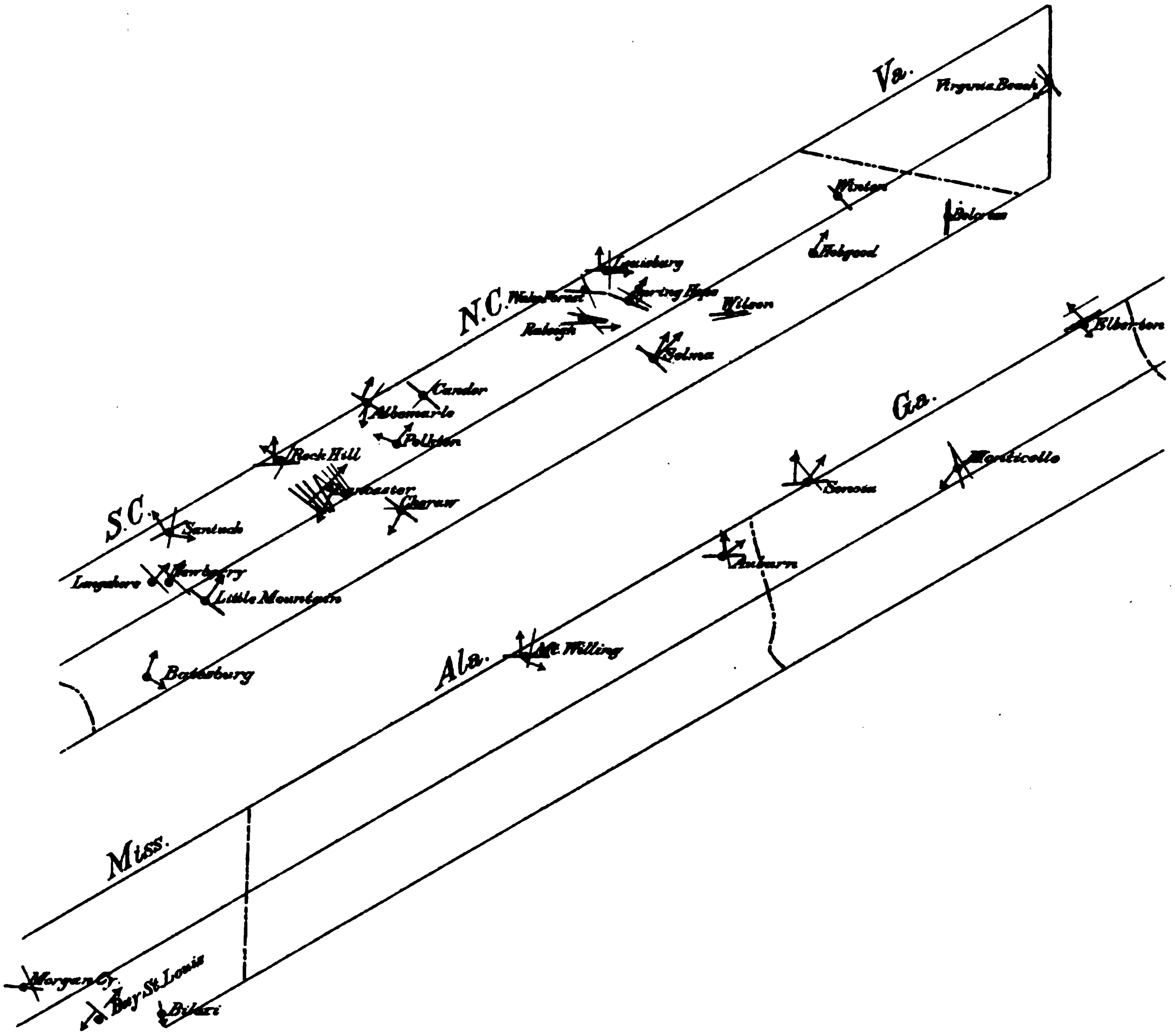
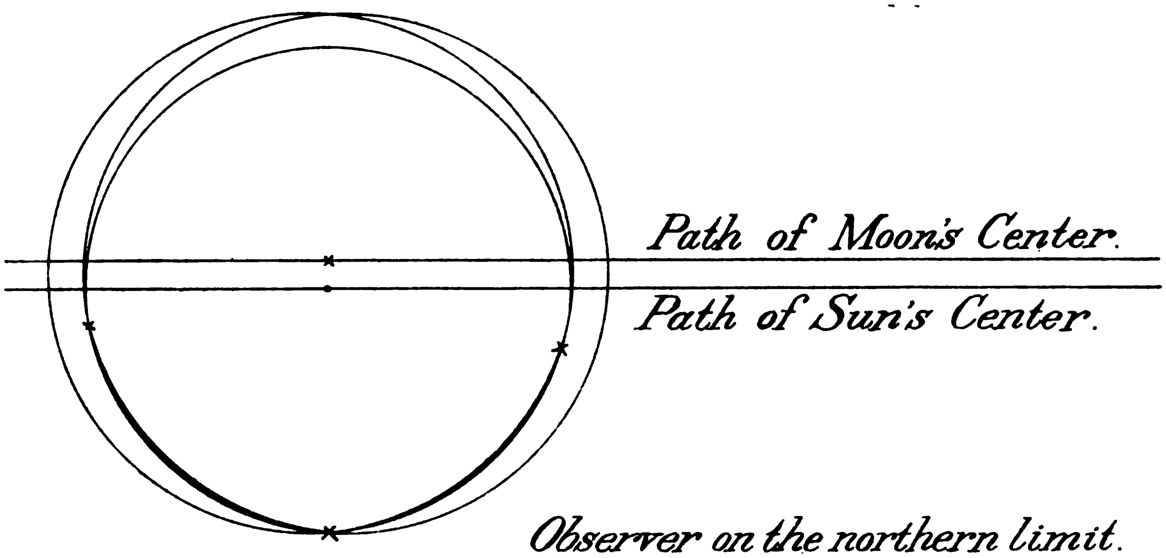
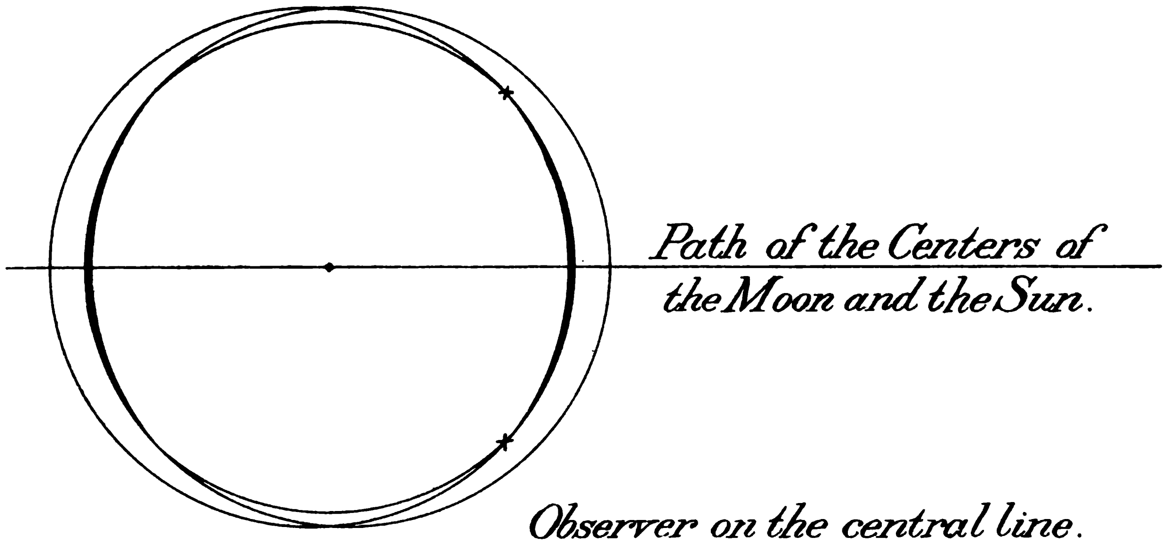


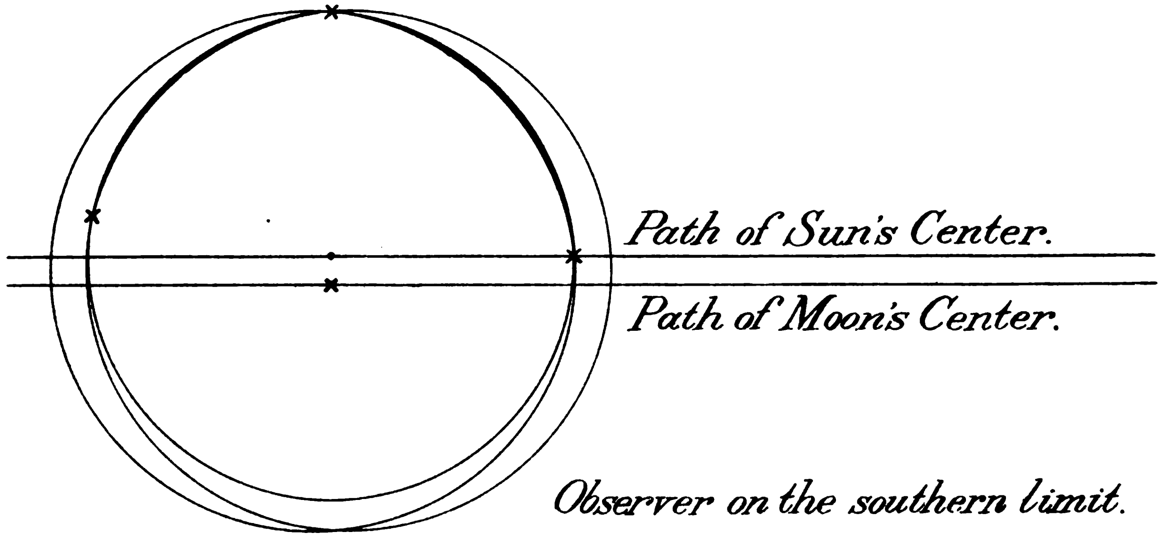
CHART 15. **Diagram illustrating the formation of the angles of the crescents.**



Observer on the northern limit.



Observer on the central line.



Observer on the southern limit.

Now, it must be remembered that according to the theory suggested above for the origin of the bands, namely, the images of the solar crescent seen through a congested semiobscure medium around the edge of the umbra, the object was not the same before as after totality, since two crescents, the first disappearing and the second appearing, are concerned. From the astronomical data of the eclipse it is found that these make an angle of several degrees with each other, varying of course with the distance of the observer from the central line. This can be verified experimentally by passing two disks of the proper dimensions over each other in positions corresponding to those occupied by observers occupying stations located first in the center, and then at greater distances northward and southward to the limits of the shadow. Compare Chart 15, illustrating the formation of the angles of the crescents.

Since the majority of our stations lay to the north of the central line, we should have a mean angle of several degrees depending upon this average distance. Specific results can not be given unless by an extensive geometrical computation involving the station coordinates.

THE ANGLES FORMED BY THE CUSPS OF THE SUN WITH THE PATH OF THE MOON, AS SEEN FROM DIFFERENT POINTS IN THE PATH OF THE TOTALITY.

The angle which a disappearing crescent before totality, or an appearing crescent after totality, makes with the line of the motion of the center of the moon's shadow depends upon the relative position of the observer within the shadow. If he is located on the center so that the center of the sun and moon coincide, the cusps are perpendicular to the line of motion. If he is on the northern edge, the center of the moon appears south of the center of the sun, and the crescent makes an angle of about 60 degrees instead of 90 degrees with that line. If the observer is on the southern side, the angle varies from 90 degrees in the opposite direction. The diagrams on Chart 15 illustrate this fact.

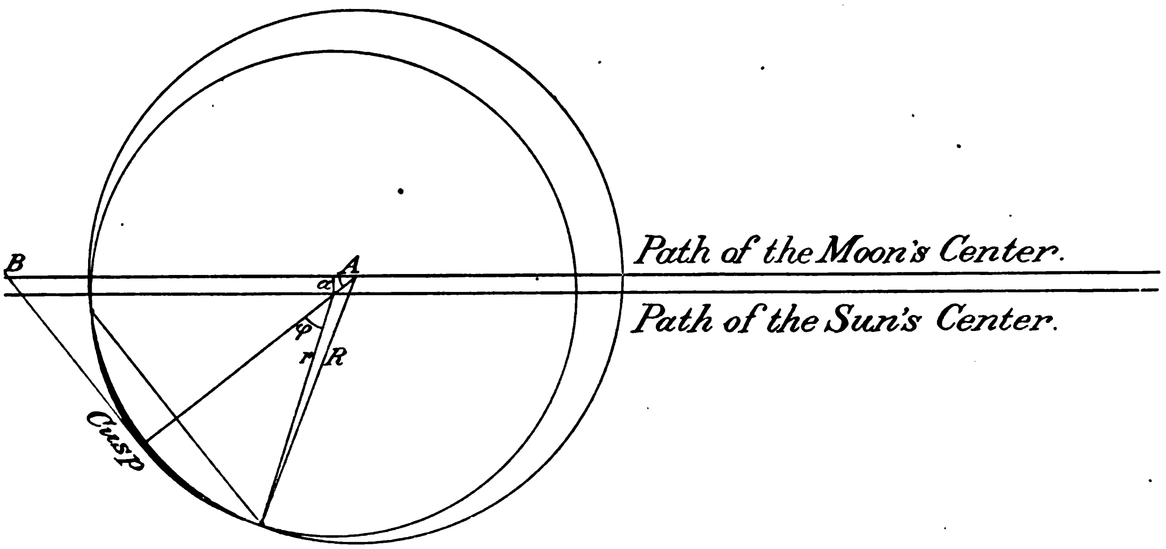


CHART 16.—Formation of a cusp with the observer to the north of the center of the path of totality.

Let r=radius of sun.
R=radius of moon.
$R-r$=radius of the path when the observer is on the northern or the southern limits.
a=the apparent distance of the observer from the center of the path.
These distances on the earth are proportional to the apparent distances on the disk of the sun.
φ=semiangle of the cusp.
A=the angle of the radius to the center of the cusp with the line of motion of the moon's center.

Then $(R-r)\cos\varphi$ = the approximate distance of the centers. Hence $\sin A=\frac{a}{(R-r)\cos\varphi}$. When the arcs of the sun and moon are tangent $\varphi=0$, $\cos\varphi=1$, and $\sin A=\frac{a}{R-r}$. Since φ changes very rapidly during the last few seconds of the visibility of the cusp, therefore $\cos\varphi$ increases, $\sin A$ diminishes, so that the vanishing arc of the cusp is located closer to the central line, since the angle A is smaller. The ratio $\frac{a}{R-r}$ is the relative distance of the observer from the center of the path. By giving several values to a the position of the point of tangency on the limb is found, and thence the angle that the cusp makes with the line of motion. This treatment of the problem was suggested by remarks in a letter from Mr. ROBERDEAU BUCHANAN, of the Nautical Almanac Office.

TABLE 13.—*The angles of the solar cusps with the moon's path, depending on the observer's place in the shadow.*

$\frac{a}{R-r}$	A		B	
	°	′		
0.0	0	0	90	0
0.1	5	44	84	16
0.2	11	32	78	28
0.3	17	27	72	33
0.4	23	35	66	25
0.5	30	0	60	00
0.6	36	52	53	8
0.7	44	25	45	35
0.8	53	8	36	52
0.9	64	9	25	51
1.0	90	0	0	0

There has been inserted on the Chart 13 of the shadow bands an inner circle whose radius is divided into ten equal parts parallel to the diameter of motion. The chords cut the circle in points corresponding to those of the tangency of the cusps; the tangents of those points give the direction of the cusps. These can be compared with the direction of the shadow bands as observed, care being taken to compare the tangents on the small circle with the bands on the large circle which have the same proportional distances from the center. Except on the south side of the path the agreement is quite satisfactory. When one attempts to reduce such observations to geometrical angles, there is necessarily the admission to be made that the original measures of the observed angles are very rough, and that only crude results seem to be obtainable. Possibly an exhaustive collection of all shadow-band observations heretofore made in other eclipses might serve to elucidate further the view which is here proposed.

In studying the direction of the bands on the circle one receives the impression that they are more uniformly placed parallel to the same direction near the central part of the path both preceding and following, but that there is a tendency to confusion, or at least to a radical change in direction for the stations located near the edge of the path, as seen near the double dividing line, especially on the northern side, where several stations secured more and better observations. In order to bring out this fact clearly the observations are also plotted on Chart 14, where those occurring before totality are printed in black ink and those after totality in red ink. They are placed near the geographical position of the station in the path of the shadow, preserving the relative distance from the center as nearly as possible. It is noted that the black and red bands near the middle of the path are generally quite parallel to one another, but that near the edge they make a distinct angle with each other. The confused direction near the limit is due to the optical effect of the shadow cone where the interval between the two contacts is brief and the sunlight even continuous.

Thus at stations near the center of the path a distinct interval elapses between the second and the third contact, which grows shorter and disappears at the northern and the southern limits where the duration of the totality approaches zero seconds. It is evident that such stations near the center, as Virginia Beach, Va.; Spring Hope, N. C.; Raleigh, N. C.; Lancaster, S. C.; Little Mountain, S. C.; Monticello, Ga., show the two directions much more nearly parallel than do Louisburg, Candor, Albemarle, in North Carolina; Rockhill, Santuck, in South Carolina; Senoia, in Georgia; Auburn, Mount Willing, in Alabama; Morgan City, in Mississippi, all on the northern side. The data do not suffice on the southern side to discuss the point in that region. The observer at Albemarle, N. C., on the extreme northern edge, remarked:

> The shadow bands moved to the northeast before totality, and to the southwest after totality. They began to flicker across the ground just before the second contact, coming from the direction indicated, and changed rapidly around by the west to the northeast without stopping.

Here something of the change in direction was noted as a continuous motion, which might be the case if it is the images of the two separate cusps which is thrown upon the ground in close succession. The following consideration makes this clearer. The angle of the cusps with the north and south line is not the same for all observers. For stations near the central line the first and second cusps appear to make about the same angle with any given direction; for stations near the northern limit the cusps make a considerable angle with each other and are no longer parallel; for stations near the southern limit they make a similar angle, but in the opposite direction. It should be remembered that all observers do not see the same cusps on the sun, but those observed at any station depend upon the relative distances of the observer to the axis and edges of the cone. A few experiments with two disks, one a little larger than the other, will bring out this feature of the case. It seems to me that this fact of the variable angle of the observed cusps before and after the totality is clearly verified by the observations on the northern side of the path, those on the southern side being insufficient for this purpose.

FURTHER REMARKS ON THE FORMATION OF THE SHADOW BANDS.

We have thus far derived two facts to fasten the bands upon the images of the cusps as the origin of them: (1) Referred to the north and the south line, the direction of the cusps and the shadow bands are generally parallel to each other, and (2) this direction varies distinctly between the center of the path and the edge, yet keeping up the same parallelism during the local change between the cusps and the shadow bands. If these two geometrical facts are the correct result of this analysis of the observations, they are practically decisive in regard to the origin of the bands. Referring again to Tables 11 and 12, it is seen that the mean velocity of motion of the bands before totality was 6.6 feet per second, and after totality it was 6.3 feet per second, the average being 6.45 feet per second. This is a surprisingly small velocity from every point of view. Some observers even hinted that in their opinion the flickering motion did not seem to move forward with any assignable velocity, but was more like a forward and backward motion. Prof. J. T. Coleman, of the South Carolina Military Academy, Charleston, S. C., who had made elaborate preparations with several assistants to record all the features of the phenomenon, stated in his report:

> The point which was uppermost in our minds was that the bands would move forward with a definite speed. When they appeared, some of the students lost much time in deciding what they should do. The student with the stop watch could not decide that he should run at all, nor did he do so either before or after totality; neither did anyone whose duty it had been made to do so.

Mr. Greenleaf W. Pickard stated:

> Some little difficulty was experienced in determining in just what direction the bands were moving; that is to say, whether southwest or northeast.

The observers generally agreed that the motion was either slow or else indecisive in direction. Now, all this is quite positive against the diffraction theory of the origin of the shadow bands. The umbra on that view is surrounded by a fringe of diffraction bands disposed in circles around its center and necessarily borne along at the same speed as the shadow of the moon, since the diffraction phenomenon must be due, if it exists, to secondary waves formed at the edge of the moon, according to the usual physical principles. The shadow moved from New Orleans, La., to Norfolk, Va., about 1,000 miles, in 25 minutes Greenwich mean time, so that the rate is 40 miles per minute, or 2,400 miles per hour, which is equal to 3,500 feet per second. If they had any such velocities, the diffraction bands could by no means be detected by our observers, and certainly they would not be recorded as having velocities of only 6 feet per second, with a flickering unsteady motion. Furthermore, the diffraction bands must, if they exist, consist of colored or spectrum fringes, but nothing of this kind has ever been detected. We therefore dismiss the diffraction theory from further consideration.

The columns of Tables 11 and 12, giving the times of the beginning and ending of the visibility of the bands, are less satisfactory than could have been desired, owing to the difficulty of observing so brief a phenomenon. After excluding a few results, as shown by brackets, the mean is a duration of 12.3 seconds before and 14.4 seconds after totality, being an average of 13.3 seconds. Since the duration of the total eclipse for the stations varied from about 90 seconds near the center to 0 second at the edges, we may take 60 seconds as a fair integral mean. Hence the duration of the visibility of the bands is about one-fifth that of the entire shadow. The shadow is nearly 50 miles in diameter, so that the medium which is favorable to the production of the shadow is one-fifth of 50 miles; that is, about 10 miles in thickness. We are, therefore, brought to conceive of the umbra as surrounded by semiopaque rings in the plane sections, perpendicular to the axis, of such a character that the crescents of the sun's disk will cast down images upon the ground through a flickering and wavy medium. The width of the bands was found to be on the average 1.37 inches before totality and 1.21 inches after totality; the bright spaces were 2.15 inches before and 2.24 inches after totality; the mean for the bands is 1.30 inches and for the bright spaces 2.20 inches; the total width from a given point on one band to the same point on the next band was 3.50 inches, and the ratio between the width of the bands and the bright spaces is 1 to 1.7; on a scale of 100 the ratio is 37 to 63. It must be admitted that there is some uncertainty, if not difficulty, in describing the exact action in the atmosphere close around the umbra shadow which should cause its edge to be surrounded by a semiopaque medium such as we have likened to the leaves of a tree.

A similar physical phenomenon is, however, well known. Thus, in Lehrbuch der Meteorologie von Dr. JULIUS HANN, 1901, page 17, the obscuring of the atmosphere by minor convection currents is described at length. In Astrophysics, February, 1897, page 107, on the "Effect of pressure in the surrounding gas on the temperature of the crater of an electric arc," by W. E. WILSON and G. F. FITZGERALD, it is said:

> We would, in conclusion, call attention to a cause of opacity in the solar atmosphere that is illustrated by the effect of convection currents in the long tube we were observing at high pressures. These convection currents behaved just like snow, or any other finely divided transparent body immersed in another of different refractive index. Light trying to get through it is reflected backward and forward in every direction, until most of it gets back by the way it came. The consequence was, that even the electric arc light was unable to penetrate the tube at high pressure when the convective currents were active.

Several facts have been developed that may have more or less influence in supporting this view of the origin of the shadow bands: (1) The thin crescent which is the condition of the bands appearing has so small an amount of penetrating light that any source of absorption is more efficient than in the case of ordinary full sunlight. The minute waves in the atmosphere existing under ordinary circumstances when currents are moving, and which become conspicuous under some types of cloud formation, may properly be referred to as disposing the aqueous vapor near the shadow to condense into minute cloudlets between which the images are propagated. (2) The effect of the shadow cone itself is to thrust a cool medium into one of higher temperature, as an icicle into a mass of water, so that the immediate effect is to cause circular heat waves to be set up with convection currents directed radially toward the center of the shadow. This disturbance may be felt generally to considerable distances, and one-fifth of the diameter of a cone does not appear to be an excessive distance to assign to such temperature exchanges. (3) There are certain irregularities on the moon's edge, and also there are others on the sun's disk, as shown by the light of the inner corona. If the disk of the sun were bounded by an absolutely sharp edge as a source of light, we should see a cone formed with a more nearly geometrical shadow and sharp surface at the earth. But the breadth of the inner coronal ring may play a certain part in causing the light of the sun to surround the moon's shadow with a fringe of irregular light, which would have a tendency to throw down the crescent of the true disk as an irregular shadow on the earth, as seen from the edges of the shadow itself. From these three causes we may expect to observe that the umbra changes into the penumbra by means of a turbulent ring or obscuring medium partaking in character of each of them during the time of the transition. From the foregoing we conclude that although the bands are more readily observed, yet it is the light spaces which correspond to the solar crescents and the bands to the obscure parts of the medium. This distribution evidently admits that only one-third of the medium of the ring is in an opaque condition, the rest being illuminated by the shimmering light of the solar crescent.

CHAPTER 4.

SOME RELATIONS BETWEEN SOLAR AND TERRESTRIAL PHYSICS.

GENERAL REMARKS ON THE SOLAR CORONA.

The physical nature of the solar corona continues to be a puzzle to astronomers, and theories regarding it have been proposed from nearly every possible point of view. The corona consists of two portions, the inner and the outer, the former being thin, near the sun's disk and complex in its constitution, the latter extended and consisting of very tenuous materials. Part of the coronal light is polarized and is reflected, being derived from other sources than the coronal material itself; part of the light originates in the coronal material, which is, therefore, incandescent, this being the case especially near the sun. This coronal substance seems to be fine dust, or else the debris of disrupted molecules and atoms, either derived from ejections of the sun or from meteoric sources. It is not a simple gaseous atmosphere like that of the earth. The sun must possess a definite quasi-permanent structure, which may be described as follows, according to the latest ideas on the subject.

There is a nucleus of unknown diameter, probably having some such relation to the visible surface as the earth to its cloud layers. From this nucleus rise streams of cooling material in vertical directions that terminate in a layer called the photosphere, which is the apparent visible surface of the sun. These uprising columns condense at a given average distance, but the irregularities in the upward motions give rise to certain characteristic features, namely, the granulation of the surface, the faculæ which exist in all latitudes as large diffuse streaks, but chiefly occur in the sun-spot belts, the sun spots, located in zones within 35° of the equator, undergoing periodic changes in relative number and in latitude; the prominences, quiescent or irruptive, fiery, cloud-like forms projected above the sun's visible disk, in extreme cases as high as 300,000 miles, most frequent in the sun-spot belts, but falling off to latitude 65° and increasing again somewhat in numbers about the poles. Just above the average position of the photosphere lies YOUNG's reversing layer, which contains within a thousand miles of thickness the materials that give forth the bright lines corresponding to the dark lines of the spectrum. Lying upon this reversing layer is the chromosphere, a gaseous envelope 5,000 to 10,000 miles thick, composed mainly of glowing hydrogen, with a few other metallic substances, through which the prominences are ejected; finally, the tenuous and very extended coronal appendage already mentioned. This complicated structure is now studied with increasing interest, and the difficulty of satisfactorily understanding the conflicting facts of solar physics but adds zest to the research.

The view just described is the old well-known condensation theory of the sun, which has been in vogue since the days of WILSON and HERSCHEL. On the whole, it may be said that it seems to require modification to some extent under recent modern research, and the belief is growing that it must be largely supplemented in order to account for all the facts. It is noted that this old theory deals only with the cooling and condensation of material passing up and down vertically from and toward the center of the sun, and it appeals only to the laws of thermodynamics. On the other hand, it is being widely recognized that under the conditions of enormous temperatures which prevail on the sun there must occur such processes as the dissociation of molecules into atoms, and also of the elemental atoms into more primitive subatoms. The laws of circular refraction exhibit evidences of operation, and the forces of electricity and magnetism also seem to play an important part in the physics of the sun. From all sides comes testimony regarding two facts: first, that the sun has a quasi nucleus and an apparent disk separate from it; and second, that these have a more or less permanent mechanical structure. This is a conception entirely different from the old notion of the sun as a vast structureless mass of incandescent vapor. The pressure of gravity in the sun would make ordinary gases have a stiffness like tar or pitch, and the metallic vapors near the center of the sun may well be so highly viscous as to be nearly rigid. This structure must be quite stable, because the periodic changes upon the sun's surface while going through well-defined variations are now known to be repeating themselves in a cycle embracing not only the solar substances, but also the magnetic and electric fields of the earth and the meteorological conditions that make up the weather. There was a time when hydrogen was supposed to be the lightest gas, but we now have a lighter one, helium, which occurs in the lower layers of the corona, in the earth, meteorites, nebulæ, and stars; there is coronium, having a green line in the spectrum of the corona, but not yet detected elsewhere, and apparently occupying a stratum up to about one-fourth the sun's radius above the disk; also there is ætherion, described by **Brush**, one-thousandth part as heavy as hydrogen, and it must have atoms so much smaller than hydrogen and a molecular velocity so much greater that it streams through glass and mercury as hydrogen does through potter's clay; finally, there is probably a "radiant matter" which pours forth from the sun millions of miles along the equatorial coronal rays, so delicate as to be hardly distinct from the ultimate æther of interplanetary spaces and comparable only to the ionized products of discharge vacuum tubes. With all these new forms of matter and the application of electric and magnectic forces to consider, much that was readily credited twenty years ago comes up for revision. The old argument was long accepted that because a comet's motion is not sensibly retarded on passing very close to the sun's surface there can be no material substances in that region, and that therefore there is a sudden transition from a sphere composed of true material substances immediately into a vacuum. It has been shown, however, that a comet's head may pass through a real gas under certain conditions without sensible retardation, because the friction merely strips off a thin surface shell without disturbing the motion of the nucleus; and also that such relations can exist between the mechanical velocities of motion and the wave lengths of the propagation of energy, depending on the state of the gas, as to enable a body to pass through it (the gas) rapidly without retardation. It is probable that we must abandon the comet argument for a vacuum near the sun.*

There are three other theories which may be mentioned on account of their interest and importance in the attempt to account for certain difficulties of solar physics. These are the ballistic theory, the dissociation theory, and the circular refraction theory, respectively. If the sun were simply a vaporous globe it is impossible that the disk should be as sharply defined in a circle as we observe it to be. The fine line of the sun's disk, together with the superposition of the coronal appendage, contradict each other in some respects and constitute a very hard problem to resolve.

It is sought to explain the protuberances as masses of incandescent material ejected from below the photosphere into the vacuum which is assumed to surround the sun, terminating sharply on the apparent disk. This view implies that there is no gradual diminution in the density of the sun's layers from the nucleus outward, as in the earth's atmosphere, but that at a fixed distance above it, at the photosphere and chromosphere, there is an abrupt discontinuity into a vacuum. The difficulties with this view are that such discontinuities are very seldom found in unconfined vapors and gases, but in them there is a gradual diminution to the limit. If a large mass of hydrogen vapor having the size of the earth be thrown up from the sun's disk, the space filled up by the resulting prominence would be occupied within half an hour or less. During this time the outer layers of the prominence cool by expansion, while the core remains at about its original temperature, so that a great change takes place in density from the center to the surface of the prominence, and this should produce corresponding refractions in the light; these, however, have not been certainly observed. The great irregularities measured in the velocities that prevail during the development of a prominence do not match with those that would mark a bomb thrown up as a projectile. In the metal lines of the solar spectrum upon and within the disk velocities as great as 600 kilometers per second are observed, but in the protuberances the highest velocities are only about 40 kilometers, showing that these must have a different origin from that of the velocities of the gases within the sun, as they are there tossed about in the processes of incandescence.

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* Ein Bild des Sonnenballs, A. Schmidt, Deutsche Revue, Juli, 1899.

The dissociation theory is illustrated by taking aqueous vapor, which separates into oxygen and hydrogen gases, forming oxyhydrogen gas at a high temperature. In the same way, with greater solar heat, oxygen and hydrogen atoms may be dissociated into more primitive elements unknown upon the earth. Since the coronal extension seems to be made up of elements much lighter than hydrogen, it is supposed by some that the visible disk is that surface where the chemical dissociations and combinations are chiefly taking place. The granules, faculæ, spots, photosphere, and chromosphere are appearances attending these chemical processes. There must be much truth in this view, and something of the kind may be going on at the sun's disk, if it can properly be assumed that the known terrestrial atoms do break up still further when subjected to solar temperatures. Yet it is hard to see how such a process could produce a sharp boundary at the visible surface, having considerable densities on one side of it and great tenuity of material on the other. Furthermore, since the cooling is from within outward, we should expect to find dissociated or solar constituents inside and terrestrial combinations outside the layers having the critical temperatures, but this is the reverse of the facts. Nor could the same temperature be critical for the dissociation of several different elements. In other words, dissociation ought to take place at different levels, and thus produce a gradual shading in the density outward, instead of the sharp disk which is always seen.

The circular refraction theory starts with the phenomenon that if a sphere is surrounded by a mass of gas of densities diminishing with the height, there exists a circular layer where a ray of light from the outside falling upon it at a tangent will continue to travel around the sphere in a circle at the same distance from the center. If a golden ball one inch in diameter is covered with a shell of glass one-half an inch thick, the golden sphere will seem to be magnified to a 2-inch globe by the action of circular refraction, and the glass itself will not be seen at all. In the same way, since the nucleus of the sun is smaller than the disk, it is supposed to be optically enlarged to the visible size by such a refractive action of the spherical layers surrounding the sun upon the emerging rays of light. This theory is interesting, has several points of special value, and is receiving considerable attention. The result is that the appearances on the visible sun's disk are all supposed to belong to regions one-third the radius nearer the center, and that the changes on the sun's surface noted in the telescope are more or less optical exaggerations; in fact, only secondary appearances. We therefore perceive a sharp circular disk high up in the sun's atmosphere, whereas in reality it belongs to a nucleus far below.

An important point regarding all these theories—condensation, ballistic, dissociation, and circular refraction—is that they imply that the sun has a solid or highly viscous nucleus of definite structure, capable of slow periodic movements within itself, where the energy is transformed from one state to another; also that it is being subjected to sudden quivers or shocks as this energy spasmodically seeks to free itself from temporary constraints. Much evidence has been collected to show that the earth sensitively reflects these solar influences in synchronous impulses through the magnetic and electric changes in the state of the atmosphere. This solar-terrestrial branch of physics, it is readily seen, is not only fascinating as an object of study, but it is likely to become of great practical importance if the laws controlling the physical processes can be fully analyzed. It is with the object of reviewing the recent advances in this branch of astrophysics that I have attempted to bring together the results of our knowledge on these topics. It will be shown that the meteorologist has, scientifically, much more interest in this subject than has been commonly realized, and that a new light is being thrown upon several obscure portions of meteorology by means of these astrophysical investigations.

SCHMIDT'S CIRCULAR REFRACTION THEORY OF THE SUN'S DISK.*

SCHMIDT's theory of the sun's constitution and appearance depends upon the optical phenomenon of circular refraction. If a sphere is composed of gases stratified by their molecular or atomic weights so that the heaviest are at the center, and the density decreases outward, there is a possible proportionality between the radius and the index of refraction for a certain stratum, such that a ray of light tangent to the critical layer will undergo circular refraction and remain at the same distance from the center of the body. If a ray, by reason of a larger angle of incidence at its source, escapes above this circular layer, it will make its way into space, and its curvature is less than in circular refraction, this being the type in the terrestrial atmosphere. If the ray, by reason of a smaller angle of incidence from the inner and lower strata, fails to reach the circular refraction layer and pursues its path within gases of relatively high density, it will not escape, but will recurve toward the original layers from which it proceeded, and this case may be designated solar refraction. There are two effects produced by this action of the rays, (1) an apparent magnification of the interior strata to the size of the circular refraction layer, and (2) the production of an optically sharp boundary called the disk. This is the chief purpose proposed by the theory, namely, to account for the abrupt termination of the visible body of the sun, which is doubtless a troublesome problem. It assumes that the sun is gaseous throughout, relatively quiescent, stratified by specific gravity, and that many of the observed phenomena at the visible surface are optical effects of irregular refraction processes upon the rays of light at invisible depths. The photosphere, the spots, the reversing layer, the chromosphere, the faculæ, the prominences and the corona, with the almost infinite number of differential circumstances belonging to them as indicated by the spectroscope, the camera, and the bolometer, are really observed only indirectly and inferentially.

This theory assumes an ideal sun which does not seem to conform to the established facts, so that critical objections have been urged against it which remained unanswered. Thus, (1) the evidence does not admit that the heavy metals are located near the center of the sun, while the light elements are confined to the outer layers, for, if so, the pressure upon the heavy metals would produce a continuous or at least a banded spectrum, while many of them have very fine lines. The spectrum shows such irregularity as regards density as to make it necessary to infer that the gases themselves are thoroughly mixed. (2) While the circular refraction layer is a sharp boundary, yet this implies that above it the gases diminish gradually in density out into the coronal region; on the other hand, the facts derived from the behavior of comets, from the quiescent and irruptive prominences, seem to show that there is in reality a sudden fall in density from that prevailing in the chromosphere to the coronal rarefaction, which is nearly an absolute vacuum. SCHMIDT tries to meet the objection from the comet argument, namely, that the velocity of propagation is not retarded when a long path of its trajectory passes through the coronal regions, by maintaining that a body may move through gaseous media without hindrance for two reasons. First, the friction strips off only a thin superficial layer by heat fusion, while the nucleus proceeds unchecked; second, certain relations between the velocity of propagation and wave length of transmission of energy exist in which there is no change of the velocity of motion of a solid body through a gas. These purely physical theorems are not yet proven, however, to be applicable to the case of the sun. (3) If the rays from the interior should pursue a very long path through heavy gases before reaching the layer of circular refraction, absorption of light would so far operate as to cause practical extinction. One can not escape from this point by an appeal to selective absorption, and yet leave intact so many lines in the spectra of the elements as are found in the sun, and proven to be so preserved by direct comparison with the terrestrial elements, where selective absorption certainly can not be effective. (4) The reversing layer, which by its inverted flash spectrum reveals the approximate level where originate the rays of light propagated into space and visible at the earth, is located at the base of the chromosphere, just above the photosphere. On SCHMIDT's theory, this layer is optically elevated from great depths, and it is a compound effect of spectrum radiations generated at different distances from the center of the sun. The denial in general terms of the existence of this layer will hardly be accounted competent to offset the specific spectroscopic details which the observations at several eclipses have brought together. Furthermore, these reversing spectrum lines should appear generally broadened, but this is not the case on the photographs.

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* Die Strahlenbrechung auf der Sonne; ein geometrisches Beitrag zur Sonnenphysik, von August Schmidt, Stuttgart, 1891. Die Schmidt'sche Sonnentheorie, Otto Knopf, Jena, 1893. Schmidt's Theory of the Sun, Wilczynski, Astrophys. February, 1895. Ein Bild des Sonnenballs. A. Schmidt, Deutsche Revue, July, 1899.

ANOMALOUS DISPERSION IN THE SUN'S ATMOSPHERE.

The path which rays of a given wave length traverse in an atmosphere depends upon the density and the refractive index of its successive layers. If it is homogeneous in density, the path of the ray is a simple straight line; if the density varies by a law regularly from the bottom to the top, as in the earth's atmosphere, the path is a curve of definite form; if the density is irregularly arranged, as in prismatic masses, then anomalous refraction occurs. In this case the spectrum lines may be seriously transposed from their natural arrangement and placed in a different order, even to changing the color succession usually observed. Hence, in the atmosphere of the sun, if the metallic vapors are congested in spherical or prismatical masses, instead of lying in simple horizontal strata whose density decreases from the center of the sun outward, the conditions are present for anomalous dispersion of the solar spectrum. Then the rays of the photosphere coming through the chromosphere will show a distortion corresponding to the density of the layers of the higher atmosphere through which they pass, and an observer at the earth will perceive these anomalous forms and positions in the spectrum lines.

It is known that the index of refraction varies rapidly on each side of the line of a given wave length. Thus, if the sodium D_1 D_2 lines have a given index of refraction, for wave lengths slightly greater than λD_1 λD_2 the index of refraction increases rapidly in the immediate neighborhood of the absorption line; for waves slightly smaller it decreases rapidly. Therefore the rays coming from different depths in the sun's atmosphere may be so refracted as to be practically superposed, even if not belonging to the same substance. An absorbing line of the upper atmosphere may seem to have very nearly the same position as an emitting line of the lower atmosphere, though physically independent of one another. Hence bright photosphere lines may seem to have the same places in the spectrum as the ordinary dark lines which are due to real absorptions in the chromosphere. Many apparent chromosphere lines may be in reality photosphere light refracted by anomalous dispersion. Rapid changes in the distribution of density will cause broadening of the spectral lines, irregular forms, offshoots, reversals, and even double reversals. These are the features commonly seen in the sun spots, the reversing layer, the prominences, and the chromosphere. These rapid changes in the visual spectral lines have been generally attributed to DOPPLER's principle of motion in the line of sight, but excessive linear velocities have been required to account for the observed displacements. Anomalous dispersion is equally capable of producing the variations noted in the form, length, and position of the spectrum lines, and it is very probable that both of these principles are in fact operating in the sun's atmosphere, thus relieving the DOPPLER principle of its too heavy burden. Thus, part of the spectrum may actually arise from emission in the chromosphere, and another part by anomalous refraction from the photosphere to make up the known chromosphere lines.

These phenomena have been reprodued in laboratory experiments by W. H. JULIUS,* R. W. WOOD,† and H. EBERT;‡ also in part by H. BEQUEREL.§ These experimenters imitate the flash spectrum of the reversing layer, many of the characterics of the sun-spot spectra, and the leading features of the prominences, by simply passing the light of a continuous spectrum through layers of a gas varying rapidly in its density and having a form approximately prismatic in outline. The wave lengths which are very close on either side of those of an emission line, though actually coming from a different substance, are the ones causing this phenomena by the action of anomalous refraction, and therefore many things which have hitherto been attributed to motion in the line of sight must receive a new critical examination. The subject of refraction in the solar atmosphere will probably merit an increasing amount of attention in the future for the reasons indicated.

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* Astrophys., October, 1900.

† Astrophys., January, 1901.

‡ Astron. Nachrichten., Mai 1901, No. 3708.

§ Compt. Rend., 127, p. 899, 1898; 128, p. 145, 1899.

THE CONDENSATION AND DISSOCIATION THEORY.

The common view regarding the formation of the disk of the sun is that it is generally a region characterized by abrupt changes in its constitution, a locus of physical condensation of metallic vapors to saturation under the conditions of pressure, temperature, and vapor tension prevailing at that level of the sun, the analogous problem on the earth being the formation of clouds of aqueous vapor; also it is a region of chemical dissociation and recombination of the elements. Specimen papers on this subject may be found in Anwendung der Mechanischen Warmetheorie auf Kosmologische Probleme, A. **Ritter**, 1882; Mathematical Spectral Analysis, R. von **Kovesligethy**, A. N. No. 2805; The Remarkable Relation between the Spectrum of Aqueous Vapor and the Line Spectrum of Hydrogen and Oxygen, as well as the Chemical Structure of the Two Last and Their Dissociation in the Sun's Atmosphere, A. **Grunwald**, A. N. No. 2797; On Solar Physics, J. F. **Hermann Schultz**, A. N. No. 2817. These papers all make the sun to consist essentially of a nucleus of some sort surrounded by a layer of special chemical activity at a considerable distance above it, the total mass of the material of this structure being equivalent to that computed by astronomical laws. Another modification of the last view is that the isolated superficial layer is the seat of intense electrical currents and discharges, causing dissociation of the molecular material and emitting streams of radiant matter into the coronal regions. At the same time the nucleus is the seat of intense magnetization, and the field of magnetic force depending upon it influences the visible aspect and curvature of the coronal extensions. This is the view which has for many years seemed most probable to me, and it is the one toward which I have devoted my efforts with the object of gaining definite evidence in its favor. Before returning to its discussion it will be desirable to continue our review of the recent theories of the sun in order that all the important facts may be before us previous to drawing our final deductions. At present it is proper to state that, in the opinion of most astrophysicists, **Schmidt** does not seem to have satisfactorily made his theory of the sun include many indisputable facts, and that in consequence of this failure the theory of the simple gaseous structure of the sun, which has satisfied some astronomers, has met with a serious reverse. If the gaseous constitution of the sun breaks down in its most elementary form, it is next in order to try the hypothesis of a viscous nucleus surrounded by a more or less distant concentric spherical shell, the seat of condensations, of chemical dissociation and recombination, of electrical currents and electrostatic forces, of atomic radiant energy, while at the same time the nucleus is the seat of a magnetic field of force.

THE PHOTOSPHERE AND SOLAR SPOTS.

The problems of the relation of the solar spots to the photosphere, and the cause of the darkness of the spots, instead of being satisfactorily explained as a result of the evidence derived from observations of various kinds, seem on the other hand to have become even more bewildering than they were some years ago. This no doubt in part is due to the fact that the phenomena are more complex than was supposed, and that more is now known about the details involved which must be explained along with the account of the general theory. Furthermore, the results of the observations are very contradictory; this may be explained, at least in part, by supposing that the sun spots do not rigidly conform to a single type, but really exist under different physical aspects sufficiently divergent from each other to afford inconsistent evidence, unless this is classified with regard to more special subdivisions in the general point of view.

The facts made known by different observers which seek for reconciliation in the scientific explanation of the processes in the sun, signalized in the spot phenomena, may be summarized as follows: The spots undergo decided variations in their relative frequency in the so-called eleven-year period, which, however, fluctuates considerably about the mean duration of the cycle in intensity or amplitude. The spots at the beginning of the minimum of the period form in four belts, two each side of the solar equator, one of these in either hemisphere near the upper limit in latitude, which is about 35°, the others quite near the equator. The belts nearer the poles consist of a fresh irruption of spots, while those close to the equator are the remnants of the period which is passing off, since in the eleven-year period the mean spot belts gradually descend from higher latitudes, approach the equator, and there disappear. Hence at the maximum of the period the spots occupy the middle zones near latitude 14°. The drift in longitude is greatest at the equator, where the period of rotation of the solar surface is 24.86 sidereal days. Toward the poles this gradually reduces to about 27.50 days in latitude 45°. It is not known with certainty what the angular velocity is at the poles of the sun, but it is probably the same as at the equator, so that the velocity of middle latitudes indicates an antirotational draft, being slower than at the equator and poles. The spots themselves appear to consist of masses of metallic vapors and gases which are cooler than the surrounding photosphere and strongly absorb the solar radiation. The majority of the observations indicate that they are true depressions in the photosphere, the curvature being concave downward; other observations on the contrary seem to show that they are elevations above the photosphere and have their surfaces of equal density convex upward. De la Rue, Loewy, Stewart, Secchi, Ricco, and many others confirm the Wilsonian or depression theory; Howlett, Spoerer, Perry, Ranyard, Whipple, Sidgreaves, and others maintain the elevation theory. Besides these contradictions from direct visual observations, we have equally divergent testimony from the spectroscopic results of measures on the width and position of the spectral lines. The same lines which are seen in the photosphere usually run across the spectrum of the penumbra and the umbra of the spot. Some of these lines are widened in the umbra and undisturbed in the penumbra; some are widened in the penumbra but are not modified in the umbra; others are reversed throughout both portions of the spot; the majority of lines, however, are the same in the photosphere and also in the spots. These changes may arise from relative motions in the line of sight, from local variations in the pressure and the temperature, from absorption in superposed layers, and from the action of a magnetic field upon the electrically ionized charges whose oscillations are supposed to emit and cause the spectral radiation. The only conclusion to be drawn is that a sun spot is the locus of extremely active operations of many chemical and physical forces, and that these processes indicate an especially complex and turbulent field of action.

More positive testimony as to the relative elevation of the sun spots is given by the results of observations by Stratonoff, Belopolsky, Wolfer, and some others, who affirm that the order of relative angular velocity in longitude increases upward, that of the spots being greater than the photosphere and less than the faculæ, so that the order of elevation is photosphere, spots, and then faculæ. Passing over the rather natural surprise one feels at supposing the spots to drift over the photosphere—like clouds over the underlying regions of the earth—because they are floating in a stratum having a different relative velocity of motion, it may be remarked that the fact, if accepted, of greater velocity of the spots may not necessarily be interpreted as pertaining to a higher elevation. If the solar spots have any analogue in terrestrial meteorology, it is in the cyclones which drift about within their proper stratum, through the action of the local currents that generate them. We should need assurance that no horizontal currents exist at the level of the photosphere, and this is not likely to be true, before the above conclusion is accepted as a necessary inference. Wilsing and others state as the result of their observations, moreover, that the spots and the photosphere do not have a different rotational drift in longitude. Again, Langley, Frost, and Wilson find that while the thermal radiation from the center of the sun's disk decreases by a certain law to the limb in consequence of the absorption in the thicker layers through which the rays pass at the limb, yet the thermal radiation from the spots does not diminish quite so rapidly as that of the photosphere. This could be explained by an elevation of the entire spot above the photosphere, or else by a partial elevation of the upper portion of the spot over the level of the photosphere, such as Hale has suggested. Also some spots seem to radiate more vigorously than the adjacent photosphere, and from this it is inferred that there is less absorbing material lying above them, and that, therefore, they must be somewhat elevated. Finally,

Cortie states that certain umbra have been seen on the limb of the sun to pass off at a distinctly higher elevation than the photosphere itself. Allowing for the difficulties of this contradictory evidence, we are inclined to conclude that some spots form so that their upper portions are higher than the photosphere, but that their lower parts are always buried within the photosphere itself, and we shall endeavor to show how this may occur in harmony with the facts. Spots do not, however, always conform to this criterion, but some may be so constructed that their upper parts shall be substantially on a level with, and some spots even below that of the surrounding photosphere.

There are a few more minor features to be mentioned regarding the phenomena of spots. It has been repeatedly observed that visible masses float toward a spot center from all directions, and apparently precipitate themselves from above into the midst of the spot. The faculæ occur commonly in a sort of rough hedge around the border of the penumbra; they also float at higher levels directly over the spot, like cirrus clouds over the underlying cumulus of a terrestrial cyclonic area. **Spoerer** finds that currents sometimes converge toward a certain spotless region, and that soon thereafter a spot forms at the place of convergence. The spot structure presents a typical well-defined formation, with radial light and dark rifts over the entire photosphere. There is little if any evidence of tangential circulation within the spot itself, though an entire spot may rotate slowly about a vertical axis. The material of the spot is very quiet on a large scale as compared with molecular and other minute motions; a multitude of fine lines have been found by **Young** and others well within the umbra, which indicate rapid chemical combination and dissociation.

THEORIES OF THE FORMATION OF SOLAR SPOTS—FAYE'S, VON OPPOLZER'S, AND SECCHI'S THEORIES.

There are three general theories concerning the formation of sun spots which have received attention, namely, **Faye's**, **Von Oppolzer's**, and **Secchi's**. **Faye** used the meteorological analogue of the terrestrial cyclone, **Von Oppolzer** the anticyclone, and **Secchi**, as it were, a combination of these two types. **Faye** would generate the cyclone, with its ascending vertical circulation, by means of the differential relative angular velocity of the drift in the photosphere, which produces the right and left handed gyration, respectively, in the north and south hemisphere. This theory has never satisfactorily answered the criticisms that gyration is so rarely observed in the solar spots that it can not be an essential feature of them; that the differential velocity in the photosphere is much too small to produce cyclonic action; and that in ascending currents the upper portion is relatively colder than the bottom, while the absorption in sun spots requires this relation to be inverted, so that the layers in spots shall be colder below and warmer above.

Von Oppolzer appeals to anticyclonic phenomena in the earth's atmosphere for an analogue to the sun spots, especially to the descending current in the winter, which is characterized by an atmosphere cleared of visible aqueous vapor, through which the dark earth is visible to an outside observer, and to the strong inversion of temperature which makes the lower strata colder than the upper. He seems to think that a descending current of solar vapors where the increase of temperature is as much as 6,000° C. in 11.4 miles, or 1′ of arc, could yet maintain what was condensed in the upper layers in a state of cloudiness. This rate of adiabatic temperature change leads to impossible temperatures in the interior regions of the sun, especially in view of the fact that the latest investigations on the effective temperature of the sun's radiation makes the photosphere to be in the neighborhood of only 7,000° to 8,000° C. Furthermore, why omit to mention the summer anticyclones, in which the lowest strata, instead of being cooled near the ground, are decidedly overheated, so that the temperature gradients are exverted instead of inverted, while the earth would still appear dark, but with lower strata of greater emissive power?

If A represents the adiabatic rate of cooling, then B stands for the winter and C for the summer anticyclonic gradient. An examination of the Table 147, II, page 726 of the International Cloud Report of the United States Weather Bureau, 1899, gives the details of these two types of temperature inversion. We can not assume that the surface of the sun would, like the earth, appear dark if seen through a rift in the photosphere, and there is nothing to be gained on clearing the solar sky by descending currents. Since the earth is a better absorber and radiator of heat than the atmosphere in contact with it, the surface oscillations of temperature are much greater than they are at a little distance above it, but there is nothing to match this part of the analogue in the case of the sun. Von Oppolzer sees in the slow spiral approach of currents from the solar poles toward the Tropics the source of his anticyclonic currents. We have shown in the Cloud Report that anticyclonic and cyclonic circulations and the attendant phenomena are very shallow, compared with the total depth of atmosphere, being confined, practically, to the lowest 3 or 4 miles, and that they are always produced by the counter flow of powerful horizontal currents. It is evident that an observer outside the sun should be able to see quite a different type of phenomena from what is actually observed if the anticyclonic theory is correct.

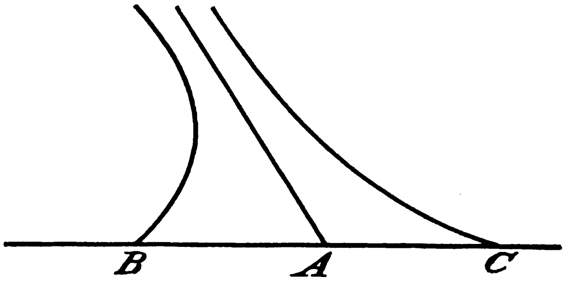

CHART 17.—Typesof inversion and exversion gradients.

Secchi explains the spots as the descending products of condensation of material which has previously been ejected from the photosphere near the spot but not at it. It has seemed to me that since the history of irruptive prominences can be so minutely observed in all details from the beginning to the end, and since all the conspicuous movements near the spots, such as the faculæ bridges, the falling of photospheric matter into the umbra, the motions in the penumbra and the umbra have been carefully described, that if any such vertical circulation as Secchi required really exists, it must be generally visible to careful scrutiny. Otherwise, several of the difficulties attaching to the Faye and the Von Oppolzer theories apply with equal force to Secchi's explanation of the local darkening of the solar photosphere.

GENERAL VIEW OF SOLAR METEOROLOGY.

The darkening of the photospheric clouds has been assigned to several causes: (1) The inability of the dissociated gases in the interior of the sun to emit radiant light, as the result of the destruction of molecular vibrations. This hypothesis breaks down, however, from the fact that such rifts in the photosphere should show a transparent opening clear through to the opposite side of the spherical envelope. (2) To the condensation of the upper layers of the photosphere by the radiation of heat to space. This theory fails quantitatively, because the radiation into space at that stratum is not equal to the supply of heat derived from the lower layers. By analogy, terrestrial clouds do not form by the radiation of heat into space, but by the expansion of currents ascending to strata of lower pressures. (3) To a screen formed by cooler gases descending from a sufficient height above the photosphere. This does not apply with sufficient generality to the solar surface, because spots should then be formed always under the debris of falling matter ejected in the irruptive prominences and other similar phenomena. (4) To electrical action, which need not be further considered as a primary cause of cloudy condensation, though we know it may modify the number of nuclei upon which the vapor is deposited. (5) To thermodynamic expansion from the unsaturated to the saturated stage, in rising from levels of a given initial pressure to those of diminished pressure. This view seems to me to be the correct one regarding the formation of the entire photosphere as a cloud shell at the end of a cooling radius, whose place is determined by the initial pressure, temperature, and vapor tension of the base of the vapor columns, which originate nearer the center of the sun. We would press the validity of the application to the explanation of the photosphere of the meteorological laws derived from the terrestrial atmosphere as regards the formation of cloud forms, especially the cumulus, which, if compacted and continuous around the entire earth, would present the appearance of wool pack and mottled forms to an outside observer, like those seen in the granulation and dark pores over the solar disk. The physics of this theory is so well known and has been so often alluded to in this connection that we may at once pass to the special point in view, namely, the peculiar type of condensation seen in the sun spots themselves. If in general the cloudy surface of the sun represents the first condensation at the end of the α stage and the beginning of the β stage, or the unsaturated and the saturated vapor stages, respectively, then we propose to see in the spots the next process in which the vaporous condensations begin to coalesce into metallic conditions akin to the formation of rain precipitation within the earth's cumulus stratum. More strictly, the analogous state in terrestrial meteorology is not the cyclonic (Faye) nor the anticyclonic (Von Oppolzer) types of middle latitudes, nor the anomalous forms of condensation by extraneous falling material (Secchi), but simply the precipitation products peculiar to the tropical regions. For these most closely represent solar conditions, with the excessive heat and vigorous evaporation, with ascending currents free from general gyration, which condense at a height determined by the three elements mentioned, and then fall back in heavy, long-continued precipitation. This vertical convection is the only natural process that prevails where powerful horizontal currents of circulation do not exist, since these are the chief causes of the existence of high and low pressure areas and their attendant phenomena in the middle latitudes. Seen from above, these precipitation areas appear darkened, as compared with the adjacent regions where local condensation has not proceeded to the stage of liquefaction.

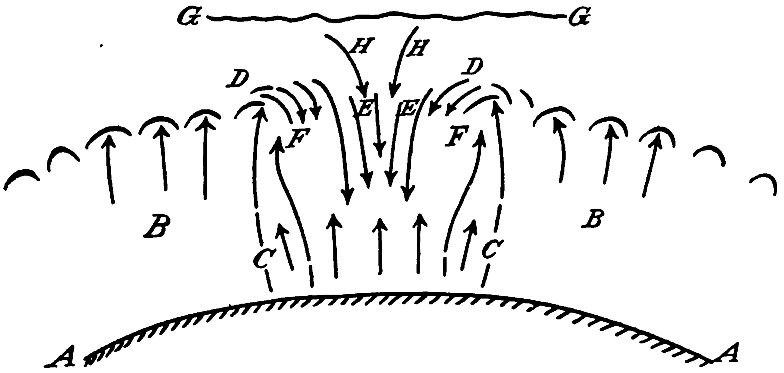

Chart 18.—Typical circulation in the formation of a solar spot.

Let *A* represent the surface of an interior nucleus of gases at very high temperature, and yet condensed to a viscous state by intense gravitational pressure, *B* the ascending currents whose heads form the cloud top of the cumulus type, *CC* especially vigorous ascending unsaturated currents which at the beginning of a spot formation may rise somewhat above the average level of the photosphere as *DD*. The true precipitation begins with a breakdown in the photosphere, the condensation products of the *DD* elevation falling back toward *AA* and carrying the cooler material in more condensed (liquid) form downward. This material begins to absorb heat in its downflow, but being in part liquid gains an increase of temperature only after the latent heat of vaporization is satisfied, and thus arrives at such levels as *EE* with a temperature lower than the ascending neighboring strata. This descending current within the body of the photosphere has such an individuality, derived from its different temperature, that it will thrust to one side the ascending elements *CC* which are rising on the periphery of the downflow *EE*. The upflow, however, must recurve at some higher level *DD* so that *CDFE* forms a local typical circulation whose energy is derived from within, not without (Secchi), in which there is calm, and no gyration (Faye), where the inner portions are cooler, consisting of a mixture of vapor and liquid returning to vapor. We mean to identify the highest parts of the recurving current with the elevated portions of sun spots seen in projection on the limb, radiating heat as if located higher than the photosphere, having about the shape suggested by Professor Hale; the inflowing portions *FF* constitute the penumbra, composed of a mixture of vapor and liquid, and thus radiating in radial streaks; the descending darkened portions *EE* form the umbra, which fails to radiate the average amount of heat, because this is absorbed in turning the liquid portions into vapor; it has a tubular form at times, or a flat form when the downflow is less violent, or even a form with convex upper surfaces when *DD* coalesces in an arch before the breakdown occurs; it displays quiescence of the gross materials as seen in the midst of the spots, but the congested molecular actions noted in the widening and thinning of the spectrum lines. Above this level may float the faculæ *GG* generally independent of the spot action; or the material just above the photosphere *HH* may converge and drift toward the umbral regions, and be drawn into it like faculous bridges which have been seen to disappear in the descending torrent. Enough has perhaps been said to indicate a theory of spot formation which includes to a remarkable degree all the details observed to be associated with them, and which also avoids many of the difficulties connected with the other points of view. This physical condensation theory is opposed to BRESTER's chemical combination theory with its train of deceptive illusions and half-truth explanations of several facts of observation; to all the theories which make the darkness of spots due to local relative overheating of the photosphere; to OPPOLZER's, where the additional heat is due to adiabatic compression of descending currents; to EVERSHED's, where additional internal heat in places with greater emissive power and higher temperature causes a general shortening of the spectrum, and shifts the wave lengths slightly toward the ultra-violet, after which a second shift backward is caused by absorption in the terrestrial atmosphere; to SECCHI's, where the absorption of light is caused by cooled gases descending from levels high above the photosphere, bringing the temperature of the upper strata with them; to FAYE's, where the ascending currents inside the photosphere must yet possess distinct cyclonic gyrations. It approximates in physical principle to SIDGREAVE's adiabatic condensation, but shows more clearly how to differentiate the structure of the photosphere from that of the penumbra and umbra, respectively, by introducing a circulation limited by the top of the photosphere and the interior nucleus. The mixture of vapor and liquid in this circuit, especially in the levels of the photosphere, has the property of maintaining a nearly uniform temperature, being that of the vaporization of the liquid drops, while the precipitation is falling back toward the nucleus through considerable vertical distances. Hence the penumbra, being the top of the recurving circulation, radiates laterally from the stream, which is seen at right angles to its course, and manifests the alternate gaseous and gaseous-liquid portions which flow side by side if not intimately mixed; but the umbra shows the same streams end on, and as they retain the temperature of the locus of liquefaction, which is near the top of the photosphere, for some distance during their descent, the umbra is the region of relative coolness as compared with the adjacent photosphere. The causes which produce special evaporation in the sun-spot belts are bound up with the general circulation of the solar material, just as the rain belt of the Tropics is the result of the earth's atmospheric movements. These two circulations can not, however, have much in common, because in the case of the earth's atmosphere the difference of temperature between the equator and the poles is the cause of powerful horizontal gradients, and the corresponding well-known general circulation over the hemisphere, with the dependent local cyclones and anticyclones; while in the case of the sun the temperature variations must be chiefly in vertical directions, which, on a rotating sphere, will produce a special type of circulation.

The phenomenon of the veiled spots which are seen in all latitudes indicates that the vertical precipitation in these cases occurs only on the under side of the photosphere, and does not penetrate the entire thickness of it except in the spot zones. This may mean that the condensation is more vigorous or else that the photosphere is thinner in the spot zones than in the other regions outside of them.

THE CONVECTION STREAMS IN THE INTERIOR OF THE RADIATING AND ROTATING SUN.

The sun is a rotating body which is cooling by radiation from the interior masses, and is permeated by convective streams which tend to restore the thermal equilibrium wherever it is broken up by changes in the heat contents. It is important to have a general conception of the form of the thermal lines of flow for the sake of governing the direction in which the physical theories must be constructed. Prof. H. VON HELMHOLTZ has entered upon this problem as regards the earth's atmosphere in his well-known paper on Atmospheric Movements.* R. EMDEN has used these equations and made an application of them to the interior of the sun with commendable success.* These papers are too complex to reproduce even as a summary in this place, but they are important for all students of the solar and terrestrial physical problem.

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* "Sitzungsberichten" of the Royal Prussian Academy of Science at Berlin, 1888, May 31, pp. 647–663." Translation by Prof. Cleveland Abbe, in his Mechanics of the Earth's Atmosphere, pp. 78–93.

Change the German notation into that adopted in my standard system, and especially as follows in cylindrical coordinates:

Angular momentum	$\Omega=\omega r^2$ to $\Omega=\omega\varpi^2$.
Radius vector from the center	R to r. (Bigelow).
Distance from axis of rotation	r to ϖ.
Axis from which angular velocity is reckoned	y to x.
Axis at 90° in right-hand rotation	z to y.
Axis of rotation	x to z.
Velocities	v to u. w to v. u to w.
In the hydrodynamic equations, pressure	p to P.
In the thermodynamic equations, gas constant	H to R.

We obtain, neglecting the terms due to the deflecting force of rotation, $+2\omega v$ along x, $-2\omega u$ along y, the equations:

$$\text{Velocities } u=-\omega y=-\frac{\Omega}{\varpi^2}y. \qquad \text{Accelerations } \frac{dV}{dz}+\frac{1}{\rho}\frac{dP}{dz}=0.$$

$$v=+\omega x=+\frac{\Omega}{\varpi^2}x. \qquad \frac{dV}{d\varpi}+\frac{1}{\rho}\frac{dP}{d\varpi}=\frac{\Omega^2}{\varpi^3}=\frac{v^2}{\varpi}.$$

$$w=0$$

It is evidently a mistake to neglect the deflecting forces in comparison with the centrifugal force, especially in view of the fact that they will determine a right-hand rotation to all vortices in the northern hemisphere, and a left-hand rotation to all vortices in the southern hemisphere, and will thus construct the filaments having opposite rotations in the two hemispheres of the sun.

The thermodynamic equations

$$\frac{P}{\rho}=RT \qquad \text{and } \frac{P}{P_0}=\left(\frac{\rho}{\rho_0}\right)^k$$

are now introduced and carried forward with θ and π as abbreviations to the forms,

$$dV+\theta\frac{d\pi}{dz}=0$$

$$\frac{dV}{d\varpi}+\theta\frac{d\pi}{d\varpi}=\frac{\Omega^2}{\varpi^3}=\frac{v^2}{\varpi} \quad \text{where } v=\text{the linear velocity of rotation.}$$

This becomes in a homogeneous layer,

$$V+d\pi=-\frac{1}{2}\frac{\Omega^2}{\varpi^2}+C.$$

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* Sitzungsberichten der mathem.-physic. Classe der Kgl. bayer. Academie der Wissenschaften, Bd. XXXI 1901 Heft III. Translation in the Astrophysical Journal, January, 1902, pp. 38–59.

For surfaces of discontinuity, $\pi_1 - \pi_2 = 0$. The equation of this meridian curve of discontinuity is,

$$V\left(\frac{1}{\theta_2} - \frac{1}{\theta_1}\right) = \frac{1}{2\varpi^2}\left(\frac{\Omega_1^2}{\theta_1} - \frac{\Omega_2^2}{\theta_2}\right) - \frac{C_1}{\theta_1} + \frac{C_2}{\theta_2}.$$

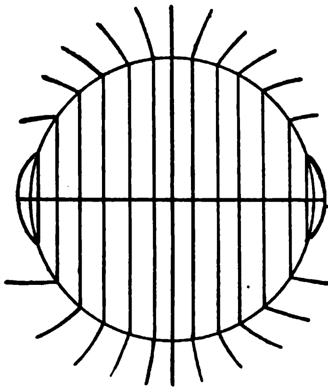
The direction of the tangent to this meridian curve is given by

$$\frac{d\varpi}{dr} = \varpi^3 \frac{dV}{dr}\left(\frac{\theta_2 - \theta_1}{\Omega_1^2\,\theta_2 - \Omega_2^2\,\theta_1}\right).$$

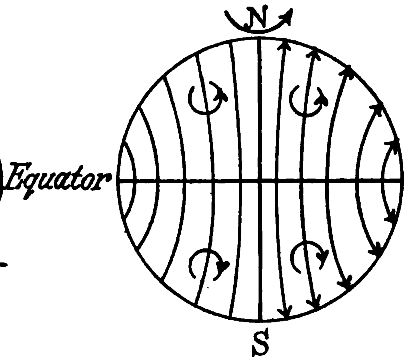
For the derivation and discussion of these equations compare von Helmholtz and Emden throughout.

It is necessary to remark that the pressure P in the hydrodynamic equations is not the same as p in the thermodynamic equations, since P is pressure in units of force of acceleration, and p is pressure as weight or mass in grams or kilometers. If the same unit system is maintained in both sets of equations, as is apt not to be the case in meteorology, then $P = G.p$ where G is the force of gravity at the place of discussion in the interior of the sun. This factor seems to have been neglected by Emden, but its introduction would only change the constants involved in θ, and not the form of the curves, so that it does not affect the conclusions.

The result of the discussion is as follows:



Uniformly magnetized sphere.



Convectional circulation within the sun.

Along the surfaces of discontinuity the convectional movement starts from the interior in waves, but these soon turn into vortices more or less columnar in general formation. They begin at the solar equator and extend toward the surface in curves which are symmetrical to the axis of rotation, but diverge from it more and more in advancing from the equator to the surface. Thus the sun is lamellated in vortical filaments at right angles to the equator, and the vortices must rotate in opposite directions in the two hemispheres under the influence of the deflecting force due to the rotation of the sun on its axis. It is not probable, as Emden supposes, that this rotation involves very widely extended areas in cyclonic whirls, such as would produce sun-spot regions, but rather that the powerful vertical convection generates small and violent vortex tubes whose axes follow the lines of the diagram approximately.

From this we make the following important deductions: (1) The true angular rotation of the sun is that at the equator, and it is the same at the poles. In the middle latitudes the angular velocity is retarded at the surface of the sun, as in the spot belts, because the convectional tubes bring up an initial angular velocity from nearer the axis of rotation on the equator. (2) From the recent development of physical researches the atoms of matter are associated with ionic electric charges, or even composed of numbers of such electrons. These move in orbital rotation like satellites, and the periodic motion of the electric charges produces a magnetic field. Compare paper by SUTHERLAND, The Cause of the Structure of Spectra, Phil. Mag., Sept., 1901; and paper by J. H. JEANS, The Mechanism of Radiation, Phil. Mag., Nov., 1901. JEANS writes:

> If an atom consists of n negative and $n+s$ positive ions, the total charge on the atom will be se, and may be referred to as the valency of the atom. * * * *Electrodynamic forces.—Permanent and induced magnetism.*—Electrodynamic forces will arise from the motions of the atoms or molecules. Each molecule of a solid will in addition to its *internal* and *translational* vibrations possess a *rotational* vibration in the field of intermolecular force. As we pass to greater amplitudes of this vibration, we shall come to a point at which a vibration through a finite angle gives place to a complete rotation. The rotation is not of uniform velocity, since irregularities are introduced by the field of force. *In a rotating atom or molecule we have the rotation of a system of charges of electricity. The net result is therefore equivalent to a circular current of electricity in the direction of rotation.* Hence in the case of vibration the result is emission of electromagnetic waves; but the force on the molecule or atom varies in direction at each half-phase. *In case of a complete rotation the current and forces are of constant direction; the atom or molecule may be regarded as a permanent magnet of moment proportional (except for irregularities) to the angular velocity, and of axis coinciding with the axis of rotation.* In general, the axes of these molecular magnets will be distributed at random, so that the solid will exhibit no magnetic properties. If the solid is placed in a magnetic field, there will be a couple on each such magnet, tending to turn its axis of rotation parallel to the lines of magnetic force.

Further effects are discussed by JEANS in his interesting paper.

The effect of the rotating vortices in the interior of the sun will be to turn the atoms and molecules around their axes, and thus to polarize them, so that in consequence the entire mass of the sun will become magnetized and generate an external magnetic field. The high temperature, great internal pressure, and the filamentary vertical convection just mentioned are highly favorable for the production of such internal magnetization in the sun. (3) It will be remembered that in my earlier researches on these subjects I determined that the synodic rotation period of the sun is 26.68 days at the poles, which is the same as that of the visible equator, while the belts in middle latitude show a distinct retardation to about 27.30 days. The parallelism between the filamentary structure of the sun and the distribution of the lines of force in the interior of a uniformly magnetized sphere, shown on the diagram, is too striking to be overlooked. The rotating masses carrying the electric charges in vortical filaments in opposite directions in the two hemispheres will generate a positive magnetic field in the northern, and a negative magnetic field in the southern hemisphere of the sun. This is in accord with the results of my discussion of the components of disturbing forces in the earth's magnetic field, which concluded that the northern hemisphere of the sun is positively magnetized. The periodic and aperiodic magnetic disturbances at the earth are consequently effects and measures of the convective circulation within the sun. It seems to me, therefore, that this view appears to overcome the objection that a hot body like the sun can not be magnetized, and that it strengthens the hypothesis that all large cosmical bodies which are cooling by radiation must also have magnetic properties. The subject thus briefly outlined is worthy a much fuller exposition, but it is necessary to pass on to further evidence which is in harmony with this theory of a magnetized sun.

THE CHROMOSPHERE, REVERSING LAYER, PROMINENCES, AND FACULÆ.

Having shown how the appearances displayed by the photosphere and spots can be explained on simple meteorological principles adapted to solar pressures and temperatures, we proceed to discuss the phenomena of the chromosphere, reversing layer, prominences, and faculæ in a similar way, by an appropriate extension to the higher regions of the sun's atmosphere. The prominences and spots occur at the level of the cloudy condensation, at considerable distance above the invisible solar nucleus, and involve primarily the processes of saturation represented by the β stage, wherein a mixture of gas and vapor reaches the pressure and temperature which changes the vapor contents of metals into liquid drops, held in suspension or precipitated according as the pure stage is retained, or as a portion of the material falls by gravitation. If these metallic substances have also a solid state, corresponding to ice in the analogue of aqueous vapor, so that they pass into liquid drops at the cumulus levels and into solids at the cirrus levels, then it will be expected that at some elevation above the photosphere there will be found in the atmosphere of the sun certain condensations resembling the formation of ice at the cirrus levels. The chromosphere is probably the extension of the purely gaseous atmosphere which rests upon the nucleus in which the photosphere floats at one level and the faculæ at a higher level, and it is seen to reach to the distance of about 6″=6 seconds of arc=4,350 kilometers=2,703 miles above the photosphere. The reversing layer is supposed to be a thin stratum of the chromosphere near the photosphere, where the conditions of the atoms and their electric charges are favorable as regards temperature and pressure for giving off electro-magnetic light waves. These are in part absorbed in the upper portion of the chromosphere and produce the Fraunhofer dark lines of the solar spectrum. This view is so plain that it is only necessary to compare the possibilities of its development with the detailed observations on the prominences and faculæ, to test the value of it in accounting for the facts. The other theories which have been recently discussed are the chemical theory of dissociation and association of the chemical elements, (1) either into primordial subatoms, or, (2) into the ordinary constituent elements of inorganic compounds; the ballistic theory of hydrogen bombs with the accompaniment of explosive expansion in free space; the incandescence and illumination of meteoric matter or solar products which collects and circulates about in the upper levels; the electrical-discharge theory in rarified gases; and the anomalous-refraction theory of WOOD at the base of the chromosphere. The chemical theory requires an atmosphere of considerable density, reaching to the uttermost extensions of the corona; the ballistic theory demands that the atmosphere should really cease at about the level of the top of the chromosphere; the minute solid particles in the incandescence theory that there be no atmosphere; and also the electrical-discharge theory that there be at most an extremely attenuated atmosphere.

The facts to be accounted for may be briefly summarized as follows: The prominences are seen to extend from the photosphere upward through the chromosphere to a distance of at least 600″; that is, one hundred times the height of the chromosphere. The forms are fantastic and extremely varied, but suggest powerful uprushes of gas, chiefly hydrogen and calcium, from below, which also falls back to the chromosphere; enormous velocities, such as 100 to 200 kilograms per second commonly, and 400 to 500 kilograms per second occasionally, are observed in the displacement of the spectrum lines. Such remarkable heights and extreme velocities are attained that it seems almost incredible that gaseous matter can really be made to pass through such transformations. Often the transitions are so sudden in their formation and disappearance as to suggest an optical appearance of temporary luminescence of tranquil matter lying in quiescent strata as arranged by gravitation; especially do the phenomena of quiescent prominences, which are destitute of violent motions and are seen to form and disappear *in situ*, seem to contradict the theory of violent eruptions. The metallic lines predominate near the base of the chromosphere, while lines of the lighter elements more frequently reach the higher strata. The observation of great velocities continued for a considerable time but with no displacement of the relative position of the prominence, is an argument against the actual movement of materials. There should be heat flushes accompanying the irregular action of congested radiation emitted from a viscous nucleus which extends upward through the atmosphere and into distant spaces. The prominences, which have a distinct columnar body, are often surrounded by a thin white sheath, forming the white prominences, which is no doubt caused by surface radiation from the column, with condensation of the gaseous material into liquid or solid states that reflect polarized light emitted from other sources. The prominences decay from the outside toward the interior, just as clouds dissolve in the earth's atmosphere. The temperature gradients on the sun are generally vertical, since it is probably radiating equally in all directions; but there are also local variations of temperature, and in consequence temporary horizontal circulations needed to readjust the disturbed equilibrium of the strata. The anomalous angular motion of the photosphere is probably due to some permanent law of radiation not yet worked out, and this can be best determined by an accurate knowledge of the rotation periods in the different strata of the sun's atmosphere after the confusion now prevailing in the measures has been cleared up. Much importance has been attached to the effect produced by the material accompanying the ascending currents when it falls back to the chromosphere, and the extreme horizontal velocities noted in the line of sight are taken to be caused by the collisions of ascending and descending streams. If meteoric matter or collections of solar dust exist in the region above the chromosphere, then they must shine in the state of incandescence to which the particles are raised by the high temperature prevailing in the neighborhood of the sun. To all these forces and conditions we must add the electrical and magnetic forces which are admitted by many students of solar physics to exist in the sun's atmosphere after the analogue of atmospheric electricity and magnetism.

Such a review of solar phenomena seems to indicate the coexistence of several typical processes, and this is natural under the very complex conditions of matter near the sun. I shall state my conclusions briefly rather than discuss each point, because it is my purpose to present the case generally, with the object of building up a view which will be valuable as a working hypothesis.

There are distinct evidences of genuine uprushes of gaseous matter attaining great altitudes and velocities, not so much due to sudden ballistic ejection as to continuous pressure along a line of escape from a congested interior region. These are the eruptive prominences, which cool from without inward in the free space above the chromosphere, deposit fine dust cooled first as a white sheath on the surface under quick lateral radiation, and then throughout the mass, which is subjected to illumination by reflected and polarized light and to incandescence by the radiation prevailing in the region. These dust particles form the nuclei of electric charges derived by induction from the region of the chromosphere and photosphere, and these produce the quiescent prominences which come and go in fantastic forms, under the variable electrostatic forces operating upon them. The enormous lateral velocities may thus be due to local electrostatic attractions and repulsions, and they may be said to resemble the phenomena in rarefied discharge tubes, for the same reasons which are applicable by known physical laws. This metallic dust can be seen at times to settle back to the chromosphere, and it may be inferred that when that level is attained, after the lapse of more or less time, the dust becomes entangled in the true gaseous envelope, and being thus held in suspension becomes the material of which the faculæ are composed. Just as the fine ice particles in the earth's atmosphere produce the cirrus formations, which remain for long periods at high levels and appear or are extinguished with the local variations of temperature and change in the state of saturation, so the faculæ have a very similar history. This material may also be supplied at first hand by the product of eruptions from the photosphere, occurring generally near the sun spots, but which does not have impetus enough to pass beyond the chromosphere. The faculæ have about the same spectrum as the prominences; they float in irregular reticulations in levels above the photosphere; they are carried about in the local currents of that region; they appear and disappear rapidly with the change in temperature as the local radiation of heat is modified; they shine partly by reflected light, partly by their own incandescence, and also in part by a sort of phosphorescent or radio-active influence from the neighboring strata, not unlike the electric glow which sometimes illuminates clouds and elevated portions of the earth's atmosphere.

The purpose of this sketch of solar meteorology in parallelism with terrestrial meteorology is to show how closely the general and the particular phenomena can be derived from the simplest possible transformation of gases and metallic vapors through the $\alpha\,.\,\beta\,.\,\gamma\,.\,\delta\,.$ stages, which are well known in meteorology. It dispenses entirely with improbable hypotheses; but, specifically, it becomes important to make the attempt to apply the laws of condensation to the solar elements. It is believed that an adaptation of the formulæ and processes developed in the International Cloud Report, Weather Bureau, 1899, to solar physics will result in at least approximately solving the questions involved. As this is a work of considerable magnitude and difficulty, we can not expect to accomplish it immediately. Meanwhile it is important to secure as definite data as is possible regarding the pressures, the temperatures at the different levels, and especially the average height of the faculæ reticulation above the photosphere. Some conception of the broad facts may be given as follows:

THE SOLAR FUNDAMENTAL CONSTANTS.

TABLE 14.—*Fundamental Constants.*

[FOR A HYDROGEN SOLAR ATMOSPHERE AND A DRY AIR TERRESTRIAL ATMOSPHERE.]

[Kilogram—meter—second—centigrade degree system.]

Formulæ.			The solar constants.		The terrestrial constants.	
				Logarithms		Logarithms
Radius		R	**696847800 m.** **433000 miles**	8.8431376 5.6364879	**6370191 m.** **3958.226 miles**	6.8041503 3.5975006
Gravity		$g_o \quad \frac{g_o \text{ (sun.)}}{g_1 \text{ (earth.)}} = 27.6$	**270.6456 m.**	2.4324010	**9.8060**	0.9914919
Coef. in lat.		k			**0.00260**	7.41497 −10
Coef. in alt.		$1+\eta=1+\frac{KM}{R}$	**1.004547**	0.0019702	**1.00157**	0.00068
Modulus		M	**0.4342945**	9.6377843−10	**0.4342945**	9.6377843−10
Weight per unit volume	Mercury	σ_m (Kilog. per cu. meter.)	**13595.8 kilo.**	4.1334048	**13595.8 kilo.**	4.1334048
	Water	σ_1	**1000.**	3.00000	**1000.**	3.00000
	Air	σ_o	**1.29305**	0.1116153	**1.29305**	0.1116153
	Hydrogen	σ_h	**0.089996**	8.9542245--10	**0.089996**	8.9542245−10
	Calcium	σ_c				
Specific weight	Mercury	ρ_m (grams per cu. cm.)	**13.5958**	1.1334048	**13.5958**	1.1334048
	Water	ρ_1	**1.000**	0.00000	**1.000**	0.00000
	Air	ρ_o	**0.00129305**	7.1116153	**0.00129305**	7.1116153
	Hydrogen	ρ_h	**0.000089996**	5.9542245 −10	**0.000089996**	5.9542245−10
	Calcium	ρ_c				
Barom. const.		$B_n=\frac{p_o}{\sigma_m}$	**20.9760 m.**	1.3217227	**0.760 m.**	9.8808136−10
Homog. Atmos.		$l=\frac{\sigma_m B_n}{\sigma_h}=RT$	**3168860 m.** **1969.085 miles**	6.5009030 3.2942533	**7991.04 m.** **4.9654 miles**	3.9026031 0.6959534
Barom. const.		$K=\frac{l}{M}=\frac{\sigma_m B_n}{\sigma_h M}=\frac{RT}{M}$	**7296570**	6.8631187	**18400.**	4.2648188
Pressure in units of force		$P_o=g_o\rho_h l=g_o\rho_m B_n=g_o\rho_h p_o v_o$ $=\frac{g_o p_o}{\sigma_1}$	**77184.22**	4.8875285	**101.324**	2.00571
Pressure in units of weight in kilo. per sq. met.		$p_o=\sigma_1\rho_h l=\sigma_m B_n$ $=\sigma_1\rho_m B_n=\frac{\sigma_1}{g_o}P_o$	**285185.5**	5.4551275	**10333.**	4.0142184
Volume		$v_h=\frac{1}{\sigma_h}$	**11.1116**	1.0457755	**0.77336**	9.8883847−10
Equ. of elasticity		$p_o v_n=l=RT$	**3168860**	6.5009030	**7991.04**	3.9026031
Gas constant hydrogen		$R=\frac{\rho_o v_h}{T}=\frac{\rho_m B_n}{\rho_h T}$	**420.552**	2.6238197	**29.2713**	1.46644
Temp. photos.		T	**7535C°**	3.8770833	**273C°**	2.43616
Temp. grad. per 1000 meters		$-\frac{dt}{dh}=\frac{1}{P_o}$	**0.0129562C°**	8.1124715−10	**9.869C°**	0.99429
Coef. of expans.		α	**0.00367** at T=273°		**0.00367**	7.56467 −10

TABLE 15.—*Computation of the relative intensity, total intensity, absolute temperature; also the temperature of a small black sphere at different distances from the sun.*

Cosec $\varphi=\frac{R+d}{R}$. Relative intensity$=\frac{\sin^2\varphi_1}{\sin^2\varphi_2}$. At earth=1.

Distance— from surface d	0''	6''	10''	17''.5	35''	175''	350''	397''.6	480''	700''
from center ($R+d$)	960''	966''	970''	977''.5	995''	1135''	1310''	1357''.6	1440''	1660''
$\log R+d$	2.98227	2.98498	2.98677	2.99012	2.99782	3.05500	3.11727	3.13278	3.15836	3.22011
$\log R$	2.98227	....	....	....	....	....	....	....	....	....
cosec φ	0.00000	0.00271	0.00450	0.00785	0.01555	0.07273	0.13500	0.15051	0.17609	0.23784
φ	90°	83 36.5	81 46.0	79 8.3	74 45.5	57 45.5	47 8.6	45 0.0	41 48.6	35 19.9
$\sin\varphi$	0.00000	9.99729	9.99540	9.99215	9.98445	9.92727	9.86514	9.84949	9.82391	9.76216
$\sin^2\varphi$	0.00000	9.99458	9.99080	9.98430	9.96890	9.85454	9.73028	9.69898	9.64782	9.52432
$\sin^2 15' 59''.63$	5.33536	....	....	....	....	....	....	....	....	....
	4.66464	4.65922	4.65544	4.64894	4.63354	4.51918	4.39492	4.36362	4.31146	4.18896
Rel. intensity	46200	45627	45231	44559	43007	33051	24827	23101	20486	15451

Total intensity of emission in gr. cal. per sq. cm. per minute. $J_o=\pi q\sin^2\varphi$; $J_o=4.0$ at upper limit of earth's atmosphere; $q=58780$.

	0''	6''	10''	17''.5	35''	175''	350''	397''.6	480''	700''
$\log \pi$	0.49715	....	....	....	....	....	....	....	....	....
$\log q$	4.76923	....	....	....	....	....	....	....	....	....
$\sin^2\varphi$	0.00000	....	....	....	....	....	....	....	....	....
$\log J_o$	5.26638	5.26096	5.25718	5.25068	5.23528	5.12092	4.99666	4.96536	4.91420	4.79070
J_o	184660	182370	180710	178110	171900	132110	99234	92334	82073	61759

Effective temperature of a plane surface $T^4=\frac{J_o}{\sigma\times 60}$; $\sigma=1.277\times 10^{-12}$ per second.

	0''	6''	10''	17''.5	35''	175''	350''	397''.6	480''	700''
$\log\frac{1}{\sigma\times 60}$	10.11464	....	....	....	....	....	....	....	....	....
$\log T^4$	15.38102	15.37560	15.37182	15.36532	15.34992	15.23556	15.11130	15.08000	15.02884	14.90534
$\log T$	3.84526	3.84390	3.84296	3.84133	3.83748	3.80889	3.77783	3.77000	3.75721	3.72634
T	7003	6981	6966	6939	6878	6440	5996	5888	5718	5325

Effective temperature of a small spherical black body $T_1^4=\frac{J_o}{\sigma\times 4\times 60}$.

	0''	6''	10''	17''.5	35''	175''	350''	397''.6	480''	700''
$\log\frac{1}{\sigma\times 4\times 60}$	9.51258	....	....	....	....	....	....	....	....	....
$\log T_1^4$	14.77896	14.77354	14.76976	14.76326	14.74786	14.63350	14.50924	14.47794	14.42678	14.30328
$\log T_1$	3.69474	3.69339	3.69244	3.69082	3.68697	3.65838	3.62731	3.61949	3.60669	3.57582
T_1	4952	4936	4925	4907	4864	4554	4239	4164	4043	3766

Distance—	1 R	2 R	3 R	4 R	5 R	6 R	7 R	8 R	Earth.	
from surface d	960''	1920	2880	3840	4800	5760	6720	7680	213.94 R	
from center ($R+d$)	1920''	2880	3840	4800	5760	6720	7680	8640	214.94 R	
$\log R+d$	3.28330	3.45939	3.59550	3.68124	3.76042	3.82737	3.88536	3.93651	....	
$\log R$	2.98227	....	....	....	....	....	....	....	....	
cosec φ	0.30103	0.47712	0.61323	0.69897	0.77815	0.84510	0.90309	0.95424	....	
φ	30° 0'.0	19 28.3	14 6.1	11 32.2	9 35.7	8 12.8	7 10.8	6 22.8	15' 59''.63	**Auwers**
$\sin\varphi$	9.69897	9.52288	9.38677	9.30103	9.22182	9.15490	9.09691	9.04576	7.66768	
$\sin^2\varphi$	9.39794	9.04576	8.77354	8.60206	8.44364	8.30980	8.19382	8.09152	5.33536	
$\sin^2 15' 59''.63$	5.33536	....	....	....	....	....	....	....	....	
	4.06258	3.71040	3.43818	3.26670	3.10828	2.97444	2.85846	2.75616	0.00000	
Rel. intensity	11550	5133	2743	1848	1283	943	722	570	1	
$\log \pi$	0.49715	....	....	....	....	....	....	....	....	
$\log q$	4.76923	....	....	....	....	....	....	....	....	
$\sin^2\varphi$	9.39794	....	....	....	....	....	....	....	....	
$\log J_o$	4.66432	4.31214	4.03992	3.86844	3.71002	3.57618	3.46020	3.35790	0.60174	
J_o	46166	20518	10963	7387	5129	3769	2885	2280	4.0	
$\log\frac{1}{\sigma\times 60}$	10.11464	....	....	....	....	....	....	....	....	
$\log T^4$	14.77896	14.42678	14.15456	13.98308	13.82466	13.69082	13.57484	13.47254	10.71638	
$\log T$	3.69474	3.60670	3.53864	3.49577	3.45617	3.42271	3.39371	3.36814	2.67910	
T	4952	4043	3457	3132	2859	2647	2476	2334	478	
$\log\frac{1}{\sigma\times 4\times 60}$	9.51258	....	....	....	....	....	....	....	....	
$\log T_1^4$	14.17690	13.82472	13.55250	13.38102	13.22260	13.08876	12.97278	12.87048	10.11432	
$\log T_1$	3.54423	3.45618	3.38812	3.34526	3.30565	3.27219	3.24320	3.21762	2.52858	
T_1	3501	2859	2444	2214	2021	1872	1751	1651	337.7	

TABLE 16.—*Summary of the temperatures and pressures at different distances from the surface of the sun.*

h=height Meters	 Sec. arc	Distance from surface	Log *h* in kilom.	ΔT	$7535-\Delta T$	T	J_0	Relative intensity	T_1 small sphere
				°	°	°			°
0	0''			0	7535	7003	184660	46200	4952
726.000	1''		2.86094	9.4	7526	7002	184621	46190	4949
4356.000	6''	Chromosphere	3.63909	56.4	7479	6981	182370	45627	4936
7260.000	10''		3.86094	94.1	7441	6966	180710	45231	4925
12705.000	17''.5	Diam. of earth	4.10397	164.6	7370	6939	178110	44559	4907
25410.000	35''.0	Top of inner corona	4.40500	329.2	7206	6878	171900	43007	4864
127050.000	175''.0		5.10397	1646.0	5889	6440	132110	33051	4554
254100.000	350''.0	Average corona	5.40500	3292	4243	5996	99234	24827	4239
288948.000	398''.0	$\varphi=45°$	5.46082	3744	3791	5888	92334	23101	4164
348480.000	480''.0	½ radius	5.54218	4515	3020	5718	82073	20486	4043
508200.000	700''.0	Limit of prominences	5.70603			5325	61759	15451	3766
696960.000	960''	1 radius	5.84321			4952	46166	11550	3501
1393920 kil.	1920''	2 radii	6.14424			4043	20518	5133	2859
2090880	2780''	3 radii	6.32032			3457	10963	2743	2444
2787840	3840''	4 radii	6.44527			3132	7387	1848	2214
3484800	4800''	5 radii	6.54218			2859	5129	1283	2021
4181760	5760''	6 radii	6.62135			2647	3769	943	1872
Earth		213.94 radii				478	4.0	1	337.7

	Height in arc	$\log\frac{h}{K}$	$\log\frac{B_0}{B}$	$\frac{B_0}{B}$	$B_0=5$ atmos. B atmospheres
	$\frac{1}{7}''$	8.15391	0.01425	1.033	4.838
	1''	8.99782	0.09950	1.257	3.976
	6''	9.77597	0.59700	3.954	1.265
	10''	9.99782	0.99500	9.885	0.506
	17''.5	0.24085	1.74120	55.11	0.091
	35''.0	0.54138	3.47842	300.9	0.002
	175''.0	1.24085	17.41200	2.58×10^{17}	
	350''.0	1.54188	34.78420	6.08×10^{34}	
	480''.0	1.67906	47.76000	5.75×10^{47}	
	700''.0	1.84291	69.64833	4.45×10^{69}	

$$\frac{dt}{dh}=-0.0129562\ \mathrm{C}^{\circ}\ \text{per kilometer (1000 m), [8.11257].}$$

$$\log\frac{B_0}{B}=\frac{h-h_0}{K\,(1+\alpha\theta)\,(1+\beta)\,(1+\gamma)\,\left(1+\frac{h+h_0}{R}\right)\,(1+\eta)}=\frac{(h-h_0)\,n}{K}.$$

$$\log\frac{B_0}{B}=\frac{h}{K}\ \text{for first approximation.}$$

Assume $B_0=5$ atmospheres$=51665$ kilog. per sq. meter.

We shall more readily reach definite ideas regarding the conditions of solar meteorology, at least approximately, by computing the constants on the sun for a hydrogen atmosphere which correspond with those on the earth for a dry-air atmosphere. This is easily done since the only changes required to pass from terrestrial to solar conditions are to make the force of gravity at the surface of the photosphere 27.6 times that at the surface of the earth, and to substitute for the weight of air per unit volume, $\sigma_0=1.29305$ kilograms per cubic meter, that of hydrogen, $\sigma_h=0.089996$. Table 14, "Fundamental constants for a hydrogen solar atmosphere and a dry-air terrestrial atmosphere," contains an exhibit of these principal meteorological relations. We are justified in taking hydrogen as the basis of the computation, because the spectrum shows that this element is most abundant in the chromosphere and up to the limits of the true gaseous envelope. Other constituents are mixed with it, as aqueous vapor and carbonic gas are mixed in the constituents of the earth's atmosphere. We may be able sometime to make the necessary modifications in order to introduce them into the formulæ. Under the columns headed

"Terrestrial constants" are given the values for the earth's atmosphere, selected from Table 64 of the International Cloud Observations. The corresponding solar constants are placed in the adjoining section. The several values are checked by an application of the numerous cross connections which are given in the formulæ, and they are therefore entirely self-consistent, so that all criticisms of the results heretofore obtained by other authors depend upon this entire body of systematic relations. All of the formulæ are well known, and the resulting values are easily verified, except the value assigned to the temperature of the photosphere to which the values are immediately applicable. From SCHEINER's Strahlung und Temperatur der Sonne, beginning with page 32, we make the following Table 17:

TABLE 17.—*The solar constant and the effective temperature of the sun.*

Authors	Year	The solar constant. Gram calories per sq. cm. per minute	The effective temperature of the sun
Pouillet	1837	1.793	° 5600
J. Herschel	1825	Same	....
O. Hagen	1863	1.9	....
Forbes	1842	2.82	....
Radau	....	1.82	....
Secchi	1860	....	5400
Violle	1875	2.590	6200
Soret	....	....	5500
Corva	1878	2.28 to 2.37	....
Langley	1884	3.068 2.630 to 3.505	6000
Rosetti	1878	....	10000
Abney and Festing	....	....	12700
Savelief	1889	2.86 to 3.47	....
Pernter	1889	3.05 to 3.28	....
Ångström	1890	4.00	....
Wilson and Gray	1894	....	6200
Paschen	....	....	5000
Scheiner	1899	....	7010

The modern reductions of the old observations and the most recent results agree in taking STEFAN's law for the total intensity of emission, which is the heat equivalent of total radiation emitted by a black body at the absolute temperature T. Compare Table 41, formula 6,

$$J_o=\int_o^\infty J d\lambda=\sigma T^4=1.277^{-12}T^4\frac{\text{Gr. Cal.}}{\text{cm}^2.\text{ sec.}}$$

where σ is KURLBAUM's value of the constant. SCHEINER's formula for computing the effective temperature is:

$$T=273\sqrt[4]{\frac{2.483}{\sin^2\varphi}\cdot\frac{J_o}{h_1}}$$

The effective temperature is that of an absolutely black body of equal apparent diameter to that of the sun and of equal radiation efficiency. The angle for a distant point d from the surface of the sun is readily computed as follows:

Let R=the radius of the sun.
d=the distance from the surface.
φ=the apparent semidiameter at the distance d.

Then, cosec. $\varphi=\frac{R+d}{R}$.

In SCHEINER's formula,

$$2.48=\left(\frac{373}{273}\right)^4-1.$$

J_o=the solar constant=4.00 gram calories per square centimeter per minute, received on the outer surface of the atmosphere.

$h_1=1.056$ the ratio of the radiation of a black body at 100° C. to one at 0° C.

$\varphi=31' \, 59''.26$ (AUWER's), the angular diameter of the sun as seen from the earth.

With these auxiliary quantities the temperature of the sun is computed to be 7003° C. This is, however, the temperature outside the sun's atmosphere, and does not allow for the solar atmospheric absorption. If this is added, it is supposed that the solar constant should be increased from 4.0 to 6.0; in this case the effective temperature of the photosphere would be 7730° C. Now, in computing the gas constant of hydrogen, we have, $R=\frac{\rho_m B_n}{\rho_h T}$. Taking $B_n=9.860$ m. and $T=273°$, the standard conditions at the surface of the earth, $R=420.552$; the corresponding conditions at the surface of the sun being $B_n=270.6456$, $T=7535°$ C., then $R=420.552$. This computation of the temperature 7535°, in so close agreement with the most probable values as derived from STEFAN's law and the solar constant at the earth, has induced me to adopt $T=7535°$ for the sake of the gas constant of hydrogen. This may be a coincidence only, but yet it serves to systematize the solar and the terrestrial constants, for hydrogen and air respectively, in a single numerical scheme. The effective temperature of a small black spherical body exposed to radiation is one-fourth that of a plane surface having an area equal to that of a circular section through the center of the sphere. This is due to the fact that the radiation received on a given area is emitted through four times that surface, since the radiation is lost equally in all directions from the sphere. The relative intensity of bodies situated at such distances that the apparent semidiameter of the sun is φ_1 and φ_2 is in the proportion $\frac{\sin^2\varphi_1}{\sin^2\varphi_2}$. The total intensity of emission in gram calories per square centimeter per minute is $J_o=\pi q \sin^2\varphi$, where $q=58780$ and $J_o=4.0$ at the upper limit of the earth's atmosphere. The temperature gradient becomes,

$$\frac{dt}{dh}=-\frac{1}{P_o}=-0.0129562° \text{C.},$$

as computed from

$$\frac{1}{P_o}=\frac{1}{g_o\rho_h l}=\frac{1}{g_o\rho_m B_n}$$

for a hydrogen atmosphere. This gradient may be used within the sun's true atmosphere setting out from $T=7535°$ at the photosphere. Finally, we have the formula for the barometric pressure at different heights:

$$\text{Log}\,\frac{B_o}{B}=\frac{h-h_o}{K(1+\alpha\theta)\,(1+\beta)\,(1+\gamma)\left(1+\frac{h+h_o}{R}\right)(1+\eta)}.$$

The term $(1+\beta)$ is due to the admixture of other gases with the hydrogen and can not be evaluated; $(1+\gamma)$ is the variation of the solar gravity with the latitude and is generally negligible in preliminary discussions; $\left(1+\frac{h+h_o}{R}\right)$ can be computed, and it is small for moderate distances from the photosphere relatively to R, the solar radius; $(1+\eta)=1.004547$; the term $(1+\alpha\theta)$ is relatively small within the sun's gaseous atmosphere, since T at the surface of the photosphere is 7535°, at the top of the chromosphere 7479°, at the distance of the outer edge of the inner corona, 35″ arc, 7206° using the gradient temperature fall; and 7003°, 6981°, 6878° for these points computed on the **Stefan** formula; or 4952°, 4936°, 4864° computed for a small black spherical body at these places. Compare Table 16, columns 6, 7, 10. We shall not commit a serious error in neglecting $(1+\alpha\theta)$ through a range of 200° or 300° at most, especially since the coefficient of expansion, which for hydrogen is 0.00367 at terrestrial temperatures, must be much smaller at solar temperatures, though I am unable to assign a value to it. The remaining term $\log \frac{B_o}{B} = \frac{h-h_o}{K}$ involves only the height and the barometric constant K. Since $K=\frac{l}{M}=\frac{\sigma_m B_n}{\sigma_h M}=\frac{RT}{M}=7{,}296{,}570$ meters, it is evident that the diminution of the pressure with the height is very rapid. If we assume that the pressure in the reversing layer, or at the surface of the photosphere, is 5 atmospheres,* as given by the spectrum shift of the lines under pressure, we compute that the pressure vanishes to a practical vacuum at the height of 35″, which is twice the diameter of the earth or about the top of the inner corona.

Table 15 contains the computation of the relative intensity at different distances from the sun, counting that at the earth equal to unity; the total emission at these distances, when $J_o=4.0$, the solar constant at the upper surface of the earth's atmosphere; the effective temperature of a plane surface, and also of a spherical body. Table 16 gives a summary of the temperatures and the pressures at different selected distances:

6″.0=top of the chromosphere.
17″.5=a distance equal to the diameter of the earth.
35″.0=the top of the inner corona.
350″.0=the average extension of the outer corona.
398″.0=the point where $\varphi=45°$.
480″.0=½ radius of the sun.
700″.0=the limit of the highest prominences.

The temperature difference Δt is computed for the height h with the gradient −0.0129562° C. per kilometer. The temperature T is from **Stefan**'s formula $J_o=\sigma T^4$; the total intensity is from $J_o=\pi q \sin^2 \varphi$; the relative intensity$=\frac{\sin^2 \varphi_1}{\sin^2 \varphi_2}$; and T_1 is obtained from J_o by the factor ¼ as indicated above. The second section of the Table 17 gives the pressure at these elevations, where $B_o=5$ atmospheres at the reversing layer, which is practically on the surface of the photosphere. It falls to 1.265 atmospheres at the top of the chromosphere, and to a vacuum at the limits of the inner corona. These facts must have an important meaning in our interpretation of solar physics.

Chart 19 exhibits the result of the computation of the effective temperatures of a plane surface and of a spherical body exposed to the solar radiation at different distances. These are marked on a line drawn through the center of the circle. The black circle represents the photosphere, the first red circle the chromosphere, and the second red circle the limit of the inner corona. The ordinates are the absolute temperatures T, and the abscissas the distance from the center of the sun, where $R=960″$, and d=the distance from the surface. At the surface temperature 7535° the gradient temperature is applied such as would occur in the solar hydrogen atmosphere. The curvature of the **Stefan** curve as it approaches its limit 7003° does not and ought not to coincide with the temperature as computed from the gradient. It is not unnatural to assume that the law of solar atmospheric absorption may be such as would be found on joining these two lines by a smooth curve as indicated by the dotted lines, since it is not probable that either of these laws continues independently of the other from the surface of the sun to distant portions of space. It may be true that we have not arrived at a perfect solution of these solar meteorological problems; but it is quite likely that they represent such an approximate approach

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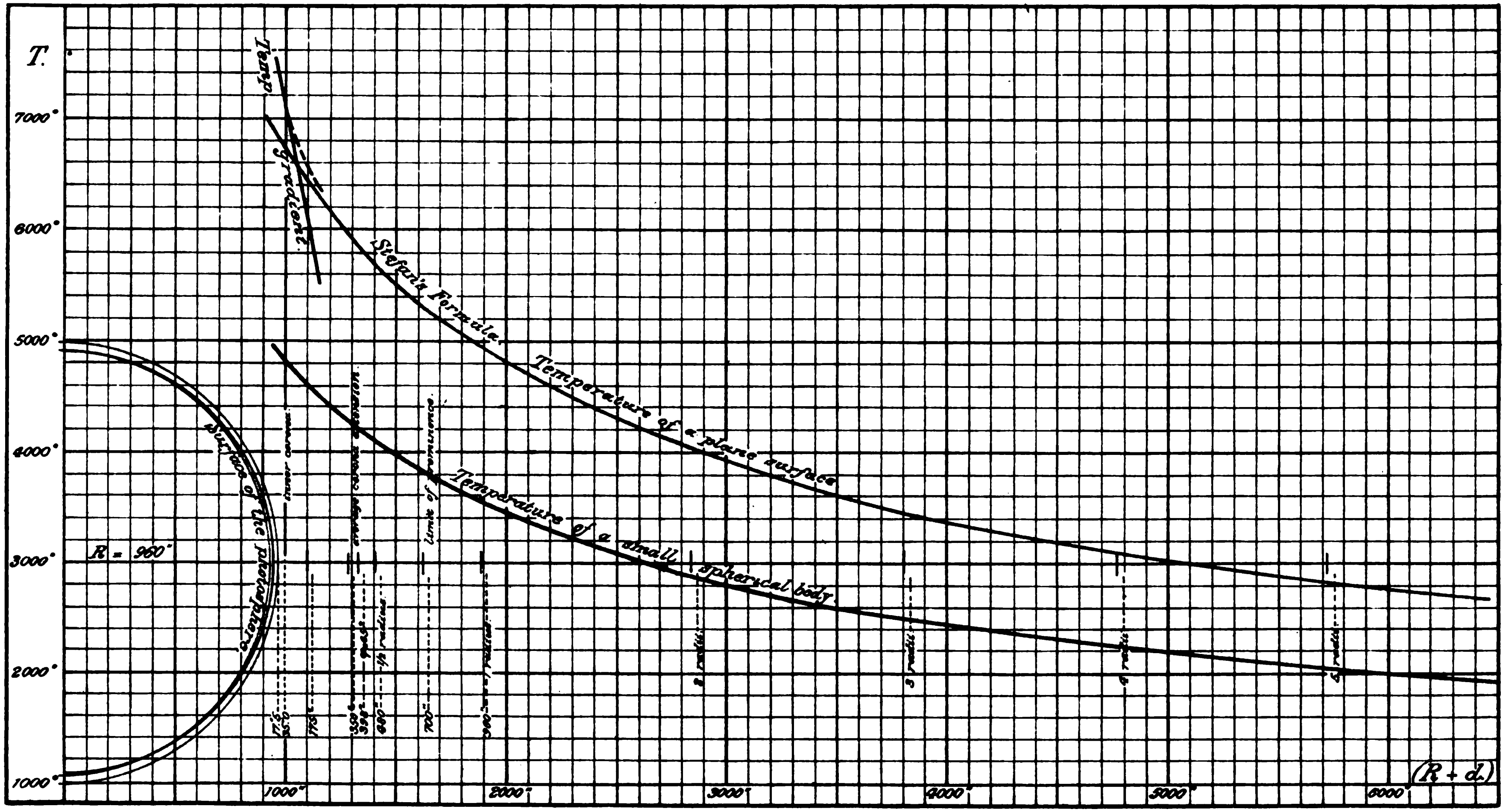
* Note on the pressure of the reversing layer of the solar atmosphere, by L. E. Jewell, J. F. Mohler, and W. J. Humpherys, Astrophysics, February, 1896, page 139. Theoretical considerations respecting the dependence of wave length on pressure, by J. Wilsing, Astrophysics, May, 1898, page 327. Absolute wave lengths, etc., by L. E. Jewell, Astrophysics, April, 1900, page 240.

CHART 19. **The temperatures of a plane surface and of a small, black spherical body at different distances from the surface of the sun.**



to the truth as will enable us to judge accurately of the value of certain statements which have been published regarding these phenomena.

REMARKS ON THE COMPUTATIONS BY VON OPPOLZER AND FENYI.

We note that since $\left(\frac{dt}{dh}\right)_e=9.869°$ C. per 1,000 meters at the earth, and $\left(\frac{dt}{dh}\right)_s=0.0129562°$ C. per 1,000 meters at the sun, and because, $g_s=g_o\times 27.6=g_o\,.\,n$, the force of gravity at the sun is 27.6 times that at the earth, we have $\left(\frac{dt}{dh}\right)_s=\left(\frac{dt}{dh}\right)_e\cdot\frac{1}{n^2}$. The first n is involved in $g_s=g_o\,.\,n$, and the second in $B_s=B_n\,.\,n$, for computing $\left(\frac{dt}{dh}\right)_s=\frac{1}{(P_o)_s}$. By the formula $\log\frac{B_o}{B}=\frac{h-h_o}{K}$, on computing K, the n appears once in $B_s=B_n\,.\,n$. We have,

$$\frac{dp}{p}=-\frac{n}{RT}\cdot dh \quad \text{and}$$

$$\log\frac{p_o}{p}=-\frac{n}{RT}\cdot h,$$

where $h_o=0$ on the surface of the photosphere.

Also, since

$$\frac{dt}{T}=\frac{k-1}{k}\cdot\frac{dp}{p},$$

$$\frac{dt}{T}=-\frac{k-1}{k}\cdot\frac{n}{RT}\cdot dh$$

$$\frac{dt}{dh}=-\frac{k-1}{k}\cdot\frac{n}{R}=-\frac{1}{\varepsilon_p}\cdot\frac{n}{R}=-\frac{1}{\varepsilon_p}\cdot\frac{nT}{l}=-\frac{n}{P_o}.$$

In these formulæ,

$$n=\frac{1}{\left((1+\alpha t)\,(1+\beta)\,(1+\gamma)\,(1+\frac{h+h_o}{R}\right)}$$

Von Oppolzer, in his computation of the solar vertical temperature gradient (Astrophysics, October, 1893, p. 738), uses $n=27.6$, $\frac{k-1}{k}=\frac{1}{3.4615}$, $R=420.552$, and finds $\frac{dt}{dh}=18.96$ per 1,000 meters, which is 1463.4 times as large as my value given above. The difference comes from neglecting to evaluate the full value of n in the temperature and the gravity terms. For 1″ arc=720.860 kilometers, this gives a range of temperature 13667°, which is an impossible result, and renders invalid the accompanying discussion.

Fenyi computes the pressure fall with the height (Astrophysics, June, 1896, p. 24) by the formula, $\frac{p_o}{p}=e^{\frac{nh}{RT}}$, or $\log\frac{p_o}{p}=\frac{Mn}{RT}.\ h=\frac{h}{K}$. However, he interprets this n as the ratio $\frac{g_s}{g_o}$, whereas the true value is that given above, and it is the variation within the solar atmosphere itself; his ratio has already gone into the construction of K. Hence, Fenyi's values of p differ somewhat from those given in Table 16.

THE ELECTRIC AND MAGNETIC FORCES IN THE SUN.

The pressure is about one-fourth as much at the top as at the bottom of the chromosphere; at a height equal to 17″.5 the diameter of a spherical volume the size of the earth it is one fifty-fourth as much; at the height of 35″ it has practically vanished, and at the height of 175″, to which prominences frequently attain, it is quite inappreciable. We may conclude that at the height of the chromosphere the pressure is diminished to one-fourth that of the photosphere, and at the outer boundary of the inner corona it becomes negligible. Beyond the inner corona the space is practically without gas pressure and is really a vacuum; the prominences therefore extend into this vacuum, though their bases rest within the region of low pressure. It is noted that the lower strata of the prominences contain metallic substances as recorded by the spectral lines, but that the higher parts show features much more characteristic of rarefied atmospheres charged with electric forces. Especially the spectrum of the hydrogen lines calls for electric action on the rarefied masses; the rapid motions in the line of sight also suggest electric repulsions between adjacent masses of charged particles. The illumination of charged particles by the radiation of the sun is adapted to produce fluorescence with a spectrum composed of continuous and fluted bands, also single bright lines. The investigation of the fluorescence of sodium and potassium vapors by WIEDEMANN and SCHMIDT (Astrophysics, March, 1896, p. 211) is pertinent to these remarks. It is here stated that our purpose is now to introduce electric discharge forces as an important agent in producing the solar phenomena above the chromosphere.

We have seen (Table 16) that the temperature fall is 9°.4 for the first 1″; 56°.4 to the top of the chromosphere, leaving it about 7479° if that of the photosphere is 7535°; 164° to the height equal to the diameter of the earth, and 329.2° to about the top of the inner corona, outside of which the temperature diminishes by STEFAN's law. We are led to consider whether there are to be found evidences of a cathodic radiation, a fluorescent radiation, and a radio-active radiation which may be properly ascribed to this particular region; and on this basis we proceed to discuss the constitution of the outer corona. The above results seem to be much more probable than those of VON OPPOLZER or of FENYI, and if they are correct, we see the way for further computations depending on these values. The upper strata of the solar atmosphere, occupying generally the region of the inner corona, are under conditions favorable for producing the phenomenon of gaseous ionization. They are rarefied to a suitable degree, are under temperatures fit for violent molecular and atomic agitations, and if, as has been assumed, powerful electric discharges take place in the solar material, then the atomic masses themselves are disintegrated, negative ions are detached, and as carriers of electricity they are propelled out into space by electric repulsion to form the outer solar corona. This view locates the electric currents in the heated gases of the inner corona, which are good conductors of electricity under low pressures, and admits the doctrine of gaseous ionization with the production of cathodic or negative carriers of electricity, or corpuscles of matter. At the same time we also hold that the solar nucleus is viscous or quasi-solid, that it is the seat of magnetization, and that the lines of force emitted by a spherical magnet can be traced in the structure of the outer solar corona. If these two systems of force exist simultaneously, a magnetic field in the nucleus, and an electrostatic field with electric discharges and ionization in the outer portions of the spherical envelope, then their interaction must produce a configuration corresponding to this physical formation. For it is well known that the negative ions are deflected from their linear path by a magnetic field, and also by an electrostatic field, as explained in J. J. THOMSON's papers. If m=mass, ϵ=the electric charge, H=magnetic field, ρ=radius of curvature, Q=quantity of electrification, W=heat energy, F=electrostatic field, θ=the deflection produced by F, and l=distance, then $\frac{m}{e}=\frac{H^2\rho^2 Q}{2W}=\frac{H^2 l}{F\theta}$.

THE EXPERIMENTAL DATA.

But we seek now a general theory rather than a special discussion of the corona, and so proceed to experimental data. It will be remembered that my investigation of the polar rays of the solar corona was based on measured positions of points (r. θ) upon the clearly distinguishable curved lines, visible in the eclipse photographs of July 29, 1878, January 1, 1889, and December 22, 1889. These are all eclipses of minimum solar activity, and are suitable for studying the polar structure of the sun, while the coronas of maximum activity show only a confused or structureless configuration about the entire periphery. These measures were discussed on the hypothesis that the polar curves are in effect magnetic lines of force seen in projection, and therefore distorted except on those rays springing from the visible edge of the disk of the sun. The work was described in the American Journal of Science, November, 1890; July, 1891; Astronomical Society Pacific, No. 14, 1891; No. 16, 1891; The Solar Corona, Smithsonian Institution, 1889; Bulletin No. 21, United States Weather Bureau, Solar and Terrestrial Magnetism. The outcome was to show that these rays conform closely to the theory, but the special point of importance to note is that the bases of the polar rays are confined to a belt about 10° wide whose central line is 32° from the poles of the sun. *In other words, the polar regions are denuded of* *visible lines of force through an arc of 50°, 25° on each side the pole, and then the rays spring up thickly in a sort of collar or ruffle quite like the distribution of the terrestrial aurora.* This fact is so important that the tabular results are here reproduced. Table 18 gives in the several quadrants of the three coronas the number of rays measured in each, and the reduction back to the invisible base of the ray for the several measured points ($r.\ \theta$) where r is the radial and θ the angular distance of the point. The majority of the rays seem to spring within 5° of the same polar distance, namely, 32°, and no rays were located near the poles. It was easy from these data to construct a small model showing the polar ruffle. The axis of the northern and the southern polar crowns is not an exact diameter of the sun, but the coronal poles are about 5° from the sun's axis of rotation, and the southern precedes the northern by about 100°. The resulting model is therefore somewhat unsymmetrical to the axis of rotation, and it was shown that by rotating the model through a certain angular distance, corresponding to the computed period and the adopted epoch, the location of the measured and computed coronal poles for at least three eclipses agreed too closely to be a coincidence. It will soon be shown that a similar procedure enabled me to forecast the corona of May 28, 1900, with success. The eclipses formed at a time which is distant from the minimum are not favorable for a close verification of such predictions. It may be remarked in passing, that SCHAEBERLE's mechanical theory of the solar corona adopts the view that the polar regions are cleared of coronal rays, but my model differs from his in this respect, that on the mechanical theory the streamers are orbital paths of projectiles thrown out near the sun-spot belts, so that his model locates the bases of the rays in latitudes 20° to 30°, while mine

TABLE 18.—*Computed polar distance of the base of the visible rays of three coronas.*

Corona of July 29, 1878. [Quadrants of rays.]				Corona of January 1, 1889. [Quadrants of rays.]				Corona of December 22, 1889. [Quadrants of rays.]			
NE	NW	SW	SE	NE	NW	SW	SE	NE	NW	SW	SE
° '	° '	° '	° '	° '	° '	° '	° '	° '	° '	° '	° '
1 30.40	1 33.5	1 35.0	1 31.41	1 37.36	1 30.22	1 32.8	1 31.44	1 33.16	1 28.33	1 30.50	1 31.35
28.35	30.17	31.41	33.25	33.46	31.28	32.39	32.40	30.22	29.27	32.21	31.30
2 28.32	30.2	30.21	29.28	33.20	29.49	30.12	31.11	27.35	28.33	30.33	31.26
3 28.43	2 28.2	2 29.22	2 30.28	2 27.19	2 30.1	2 31.1	2 27.47	2 25.31	2 25.7	2 28.9	2 32.4
32.55	27.41	31.23	32.34	29.44	30.34	29.0	27.4	25.42	24.58	27.12	33.39
30.59	26.11	30.44	3 34.25	28.18	27.59	29.27	27.17	25.27	25.28	26.37	30.4
4 31.8	3 36.30	3 33.59	34.59	3 24.45	3 32.7	3 31.29	3 29.56	3 30.33	3 29.0	3 28.14	3 61.46
33.39	34.5	32.26	31.48	24.28	33.1	32.16	30.14	31.9	29.0	28.11	31.53
30.32	32.5	30.50	4 33.45	24.45	31.7	30.53	29.51	29.57	28.59	28.18	31.24
5 32.41	4 34.52	4 30.17	34.1	4 18.38	4 32.7	4 30.27	4 32.24	4 27.25	4 26.0	4 26.56	4 31.16
33.17	33.30	31.25	31.38	17.51	33.48	30.41	33.8	27.32	25.59	27.15	31.19
31.32	32.26	30.14	5 34.1	17.35	31.0	29.25	31.17	26.41	26.4	26.46	31.6
6 33.25	5 34.24	5 33.51	34.19	5 31.17	5 33.7	5 34.27	5 33.23	5 30.15	5 34.1	5 28.58	5 32.35
33.18	35.0	35.51	33.25	30.53	34.31	35.10	33.55	30.12	34.22	29.2	32.48
34.34	34.23	33.20	6 34.52	31.29	31.57	33.26	32.46	30.17	33.24	29.31	31.19
7 36 0	33.5	6 36.33	34.54	6 38.0	6 34.14	6 29.25	6 33.24	6 31.38	6 34.13	6 34.33	6 33.4
36.23	31.29	36.35	32.38	38.25	34.36	29.29	34.50	31.42	34.32	34.50	33.31
35.16	6 41.55	35.41	7 35.8	37.3	33.33	29.5	33.10	31 9	33.40	33.52	32.12
8 42.25	41.58	7 38.59	35.13	7 43.11	31.17	7 37.49	7 34.53	7 31.28	7 34.23	7 36.40	30.33
42.23	40.49	38.57	35.11	43.5	30.4	35.53	35.31	31.39	34.31	36.38	7 33.56
40.16		8 41.6	8 39.7	42.17		36.28	32.55	31.1	34.1	36.34	33.41
		41.7	39.11			8 42.55	8 37.49	8 28.42	8 38.22	8 37.34	32.29
		40.30	38.39			43.11	37.17	28.37	38.43	37.55	
			37.26			42.2	38.30	28.48	37.37	37.25	
								9 35.59	9 39.39	36.5	
								36.0	39.40		
								35.47	38.33		
								10 38.7			
								38.24			
								37.31			
33.41	33.36	34.21	34.16	31.8	31.50	33.19	32.35	30.57	32.6	31.38	32.3
33°.59'				32°.13'				31°.41'			

are placed in latitudes 50° to 60°. I have not been able to find that the visible rays are located as near the equator as the sun-spot belts, but in fact it is evident that the rays seen on the edge of the disk, in the so-called synclinals, are not based in such low latitudes. In consequence of several doubtful physical assumptions employed by him, we can not accept **Schaeberle**'s interpretation of the data shown by the eclipse photographs.

PUPIN'S AND EBERT'S EXPERIMENTS.

It is evident that one step is yet lacking to complete this chain of argument. The discovery of the ionization of rarefied gases under numerous physical conditions, such as the radiation of ultra violet light, oscillating discharges of high tension, and so on, has put us in possession at last of an explanation of the result of my investigation of the structure of the corona which has been lacking, and for want of which the theory was without an experimental verification of its existence. The fact, however, that magnetic rays repel ionized carriers of electric charges requires exactly the effect that was found in my coronal research. If the nucleus emits a strong magnetic field whose axis is near that of the axis of rotation, the repulsion of the magnetic lines of force upon the electric charges will drive the electric rays out of the polar regions, and concentrate them in a ruffle or crown at a distance depending upon the relative strength of the magnetic and the electric forces. A proof of this fact is to be found in an experiment performed by H. **Ebert**, which is quoted in this connection. **Pupin**'s coronoidal discharges, which are well known, have attracted favorable opinion by the similarity which is shown in several particulars between the appearance of the electric discharges through poor vacuua and those shown by the coronal structure of the sun. **Pupin**'s experiment dealt exclusively with discharges from a central conducting sphere to the walls of a spherical shell surrounding it, whose surface was covered with a conducting material. It is evident that this apparatus produces vacuum-tube discharge, and that cathodic rays are produced by it in abundance. However, it is not yet strictly applicable to our theory of the sun, because it does not have a directive magnetic field superposed upon the electrical discharge. **Pupin**'s phenomenon is really a disorganized kind of general radiation, more like that seen during the times of maximum solar activity, but we require to have this unregulated structure organized into a typical form, namely, that of the magnetic field surrounding a spherical magnet, and this is to be done by superposing a magnetic field upon an electric discharge field with its cathode rays in a poor vacuum. I quote **Ebert**'s description of his experiment:*

THE ELECTROMAGNETIC THEORY OF THE POLAR-LIGHT PHENOMENA AND THE SOLAR CORONA.—H. EBERT, KEIL.

For the explanation of the most important characteristics of the polar-light phenomena the following experiments were made: Spheres, disks, and cylinders of iron and brass were exposed to the *action of electromagnetic oscillations* in spaces filled with rarefied gases; by this means their surroundings glowed, and the bodies mentioned were clothed with envelopes of light having a ray-structure, whose color and appearance was different according to the nature of the gas. *If these rays were then subjected to the lines of force of a strong magnetic field* the following phenomena were seen:

(1) If the magnetic lines extended through the rarefied region they illuminated the basal portions of the rays of light. If these disappeared, as when the gas was made too rarefied, they also appeared again when the field was strengthened.

(2) The rays of light are strongest in a field of medium strength.

(3) They follow the direction of the magnetic lines of force.

(4) When the lines of force are very dense and impinge at right angles to the surface of the iron body, *the rays of light are thrust to one side. The polar collar of the magnetized iron sphere, for example, was entirely robbed of rays; the light structure surrounds the pole in the form of a ruffle, the inner boundary of which follows the same direction as the lines of force.*

These experiments illustrate the following characteristic peculiarities of the polar light, when one assumes that the sun radiates to the magnetized earth those electromagnetic waves of which only the shortest are directly cognizable to us, that is the light and heat waves:

(1) The polar light builds itself in the thinned higher strata of our atmosphere, especially where the intensity of the terrestial magnetic field is sufficient for illumination under the action of the electromagnetic radiation, that is in the polar regions. Only in times of high solar activity does the phenomenon show more frequently and extend also into lower latitudes.

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* Versammlung deutscher Naturforscher u. Ärzte, zu Lubeck, 1895.

(2) The rays of the polar-light corona follow the lines of the magnetic force.

(3) The frequency of the polar light increases toward the magnetic pole; in the neighborhood of the pole itself where the lines of force enter and emerge in the greatest numbers nearly at right angles, they fail again.

(4) The polar light stands over a zone of greatest frequency in the form of a more or less concentric light ruffle, so that when one passes over this zone on our hemisphere, the polar lightss hine no more in the north but in the southern horizon.

The phenomena just mentioned ought to find an application in the explanation of the solar corona. In many appearances of the corona (as, for instance, in the one recently examined of January 1, 1889) numerous rays of light extend out from the polar regions of the sun, which bend toward the equatorial regions just like the lines of force of a magnetized sphere such as the earth. How the axis of the sun lies we do not know exactly, yet it can hardly be open to doubt that it also sends out lines of magnetic force into space. Among these at times of electromagnetic excitations in the interior of the sun (period of activity) the finely divided particles must in the neighborhood succeed in lighting up to considerable distances. Then the phenomenon shown in the corona comes to existence.

DEDUCTIONS FROM EBERT'S EXPERIMENT.

The experiment of Ebert forms such a fitting proof of the denuding of the polar regions of the sun as to establish a whole train of results upon a probable if not firm basis. Also, the entire subject of the interaction of magnetic lines of force with electrically charged minute carriers or corpuscles in the form of rays, has been so far developed in the last three years as to supply another missing link to the analogue, and to strengthen the magnetic theory of the solar corona. This mutual action between magnetic and electric lines becomes, then, the key to the solution of the entire range of solar and terrestrial phenomena whose explanation has so long eluded the efforts of scientists. The theory is an old one that the sun is a magnetic body and that the corona is formed by electric discharges. But so many difficulties have been thrown in the way of accepting this hypothesis from the theoretical side, and the argument that the sun must be a gaseous body on account of its average low density and high temperature, and therefore can not be the seat of even quasi permanent magnetization, have weighed so strongly with many physicists as to exclude the magnetic theory from their consideration. However, such names as the following can be quoted in favor of something of the kind, with more or less definiteness of statement: Marchand, Veeder, Pupin, Corrigan, Meldrum, Terby, Ranyard, Maunder, Sidgraves, Ricco, Ellis, Faye, Wilsing, Ebert, Rowland, Poincare, Dolbear, Huggins, and others. If the above facts as narrated are accepted as indications of the solar constitution, then we are led to the following premises for future work, and the tentative views of these scientists are placed on a fairly satisfactory basis.

1. The solar structure consists essentially of a nucleus and a distant concentric shell.

2. The nucleus is quasi solid, and it is sufficiently magnetized to emit a strong magnetic field which extends into distant interplanetary space.

3. The concentric shell is the seat of electro-magnetic radiations caused by electric oscillations of electric charges on the atoms. It is the seat of the division of certain atoms into ions which are charged with electricity and stream out from the sun along the electrostatic lines of force. It is the seat, also, of X-ray, fluorescent, and radio-active phenomena. The combination of these radiations with the dust-like particles of matter in the neighborhood of the sun produce the continuous and band spectrum and the fine lines of the corona.

4. The interaction of the magnetic field with the electric-discharge field gives the corona the special forms observed in eclipses. At the minimum activity the polar regions are robbed of rays and the equatorial extensions are most developed; at maximum the balance between these forces seems to be changed so that the electric forces of the shell predominate, together with the irregular forms of the corona.

5. The maximum of the eleven-year periodicity would seem to indicate a strengthening of the electric superficial system, in consequence of an increase of the radiations from the interior; the magnetic field also intensifies at the same time, while the balance of forces, acting on the atoms, which brings about visibility is altered so as to produce the characteristic effects observed in eclipses.

6. The system of magnetic and electric causes and effects thus outlined is such as to give the solar meteorology of cloudy condensation, and the irregular effects due to anomalous refraction

and dispension their proper proportion, so that there is no more cause for confusion regarding them than in the analogous case of the earth's atmospheric electricity and the formation of clouds.

7. If the polar regions of the sun are rich in magnetic rays and the equatorial in electric rays, and these two systems interact by a delicate balance of adjustment to produce visible coronal light, then their interaction in the 11-year period may also account for the quadrantal shape of the corona seen in the middle parts of the period. For if the electric rays consist of charged particles of the same sign, as negative in cathode rays, the mutual repulsion among the particles will produce a fan-like spreading of the lines in proportion to the distance from the surface in the direction of the ecliptic. Such trumpet-shaped extensions are frequently observed in the coronal field as well as in a vacuum tube. Hence, there are magnetic rays curved from the poles toward the equator, and electric rays curved from the equator toward the poles. These opposite curvatures operating against each other seem to be able to produce the lance-shaped forms of the corona seen in middle latitudes, so that the entire structure should seem to have a quadrantal synclinal formation at the middle portions of the period. This interplay of the curvature of the magnetic and electric fields, if correctly analyzed, is capable of affording specific data regarding the relative strength of these two fields of force, and thence progress can be made in the correlated problems of solar physics.

CORROBORATIVE EVIDENCE REGARDING THE MAGNETIZATION OF THE SUN.

(1) THE CORONA OF MAY 28, 1900.

There are yet other lines of development which in view of the position thus assumed have an increased degree of importance, and I shall briefly illustrate and summarize the results of several extensive researches in this direction.

The rotation period of the sun has been sought in many ways, but the results are in conflict with each other, so that the decision as to the final value is still withheld. From an extensive computation on the variations of the terrestrial magnetic field I arrived at the solar period 26.679 days, and computed the ephemeris from the epoch June 13.72, 1887. The best way of meeting the objections based upon theoretical considerations as to the truth of this solar period is to put it practically at work, and thus test its efficiency. This period was therefore employed to rotate the coronal model of the sun mentioned above, by applying the ephemeris and setting the model in the position assigned by the computation at the time of several eclipses. The verification depends chiefly upon the coronas observed at minimum, because the confusion of the ray structure does not permit a sufficiently close identification of the poles of the coronal streamers at other times. These poles were found to be about 5° from the axis of rotation, the south pole preceding the north by about 106°. This asymmetry between the axes of the coronal and the solar poles when seen from different points of view, as from several points in the earth's orbit, is a phenomenon easy to verify. The planes of the coronal poles were fixed by a selection of the central lines of the polar-ray structure as given by the photographs, and then these polar lines were plotted upon the well-known astronomical diagram of the projection of the poles of the ecliptic, sun and earth. By the same computation as that shown on page 138, Bulletin No. 21, Weather Bureau, the position of the model for May 28, 1900, was found to be as follows:

Computation of the longitude of the coronal poles for the eclipse of May 28, 1900.

Date of the eclipse G. M. T	May 28^d 2^h 57^m
" " " "	May $28^d.12$
Next preceding epoch of the ephemeris (epoch June 13.72, 1887—period 26.67928 days)	May 18.96
Interval elapsed, in days	$9^d.16$
" " in degrees	135.1
Longitude of the sun	66.7
Reduction to heliocentric longitude	180.0
Approximate heliocentric longitude of the south coronal pole	21.8
Approximate heliocentric longitude of the north coronal pole, being 106° behind the south pole	275.8
Heliocentric longitude of the earth at the eclipse	246.7

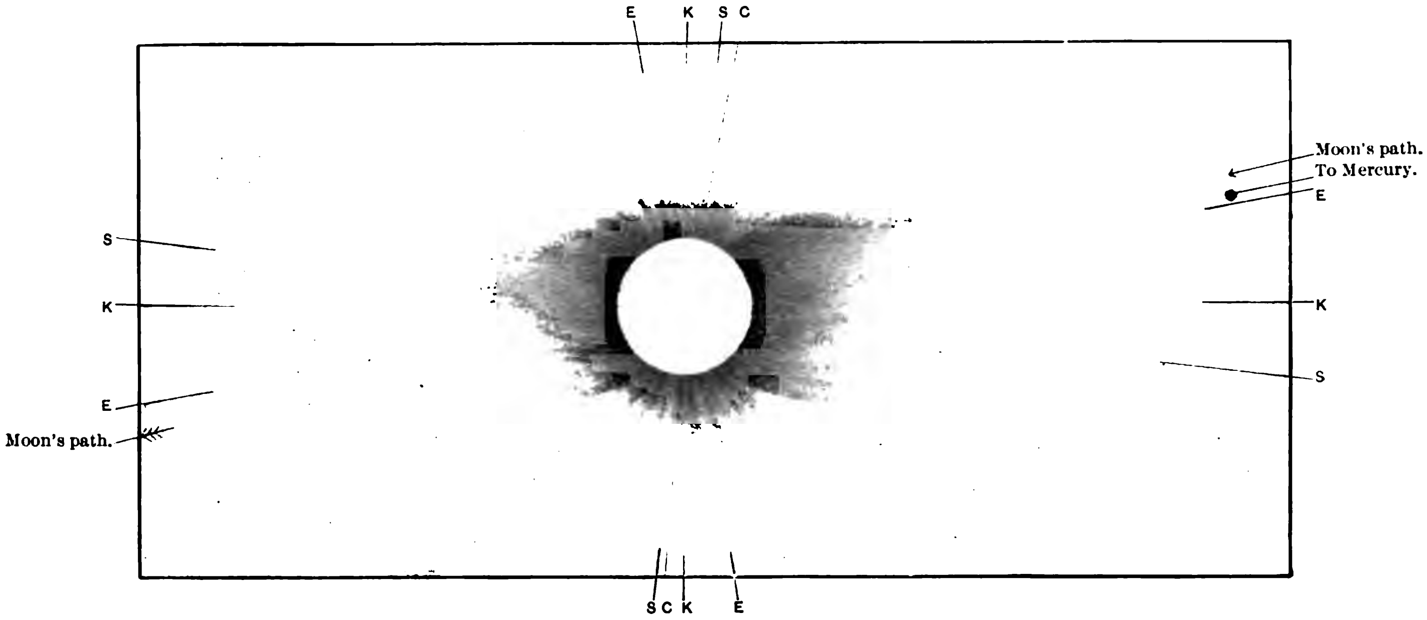

CHART 21.—FROM MR. L. E. JEWELL'S DRAWING OF THE CORONA OF MAY 28, 1900.

The north coronal pole is in heliocentric longitude 276°, while the earth itself is in longitude 247°, so that the pole C is to be seen a little to the right of S on the northern side of the disk; at the same time the southern pole C is in longitude 22°, and is to be seen about halfway between S and K on the southern side of the disk. The model thus set was photographed, and the skeleton rays about the polar regions, which show the orientation of the corona, were filled in by assuming the type of structure for the coronal extension corresponding to a minimum of the eleven-year period. This diagram was published in the *Popular Science Monthly*, May, 1900, page 9. The legend east-west was accidentally interchanged in reproducing; it does not agree with the original drawing, and it is obviously inconsistent with the system of axes, $E\,.\,K\,.\,S$. Chart 20 gives a reproduction of my original drawing, and it should be compared with Chart 21, which is a copy of L. E. JEWELL's drawing of the corona of May 28, 1900. His drawing is a carefully executed study of the coronal pictures obtained by the parties of the United States Naval Observatory at Wadesboro, N. C., and at Barnesville, Ga., and it gives the details of the corona with much distinctness. Mr. JEWELL was kind enough to lend me his original drawing to use in this connection. It was also published in Astrophysics, July, 1900. A comparison of JEWELL's drawing with the one prepared by Mr. W. H. WESLEY,* from photographs taken by members of the British Astronomical Association, shows that they agree very closely even in many details. I have marked the poles of the ecliptic K, of the sun S, of the earth E, and their respective planes. The planet Mercury appears on the extreme right of the plate; the moon's path is drawn on the picture. The special feature of interest in this connection is the position of the poles of the corona $C\,.\,C$, which have been prolonged to the edge of the disk. They are seen to agree as closely as possible with the central polar rays as determined by the general balance of the system. It is noted that the axes $C\,.\,C$ are not in the same diameter, but make a considerable angle with one another at the center of the disk. They are, in fact, both on the same side of the solar axis $S\,.\,S$. This divergence, however, matches the central positions of the polar ray structure, which would not be the case unless these magnetic poles were inclined to each other. This asymmetry of the coronal polar rays has been a persistent feature of the various coronas heretofore examined, and the unusual characteristics of this figure are repeatedly satisfied by the successive coronas from 1878 to 1900, as far as the photographs permit their examination. The probabilities are very small that this sort of coincidence occurring after many rotations of the sun can be an accident.

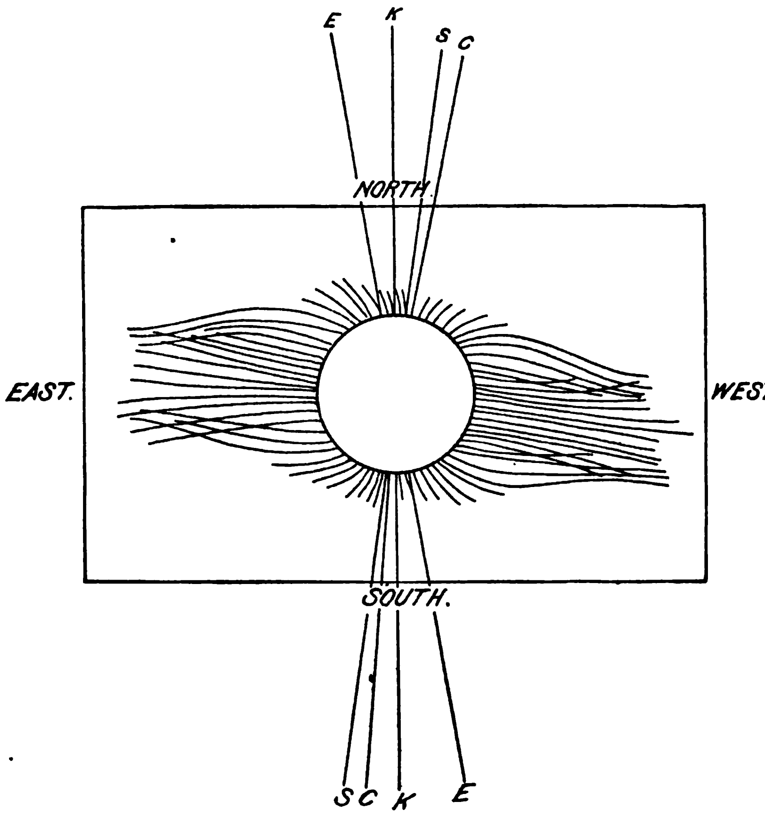

CHART 20.—BIGELOW's forecast of the corona of May 28, 1900.
E=earth's axis; K=axis of ecliptic; S=axis of sun; $C\,.\,C$=poles of the solar corona.
Original F. H. B. $KOE=9^\circ\ 45'$. $KOS=7^\circ\ 11'$.

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*The Total Solar Eclipse, May 28, 1900, edited by E. Walter Maunder, F. R. A. S.

(2) THE RELATION OF C AND C′ IN FOUR CORONAS.

On Chart 22 are seen the relative positions of the poles, K=eclipse, E=earth, S=sun, C=corona at the four eclipses, July 29, 1878, January 1, 1889, December 22, 1889, and May 28, 1900. The heavy line drawn inside the arc of the outer circle, which is employed simply to magnify the diagram and marked C, represents the position of the coronal axes as projected from the model located by computation from the ephemeris; the outer heavy line, marked C'', indicates the position of the coronal axes as determined from the photograph. The position of the axes $C''C''$ can easily be verified, but it must be done carefully by measures under a suitably mounted microscope, and these must include the entire polar region as well as the adjacent coronal rifts. If the poles of the corona rotate with the same angular velocity as that of the photosphere at the equator it means that this is the angular velocity of the nucleus, and that the photosphere drifts over the nucleus in middle latitudes with a velocity determined by the forces which control the circulation in the sun, just as the atmosphere drifts over the earth's surface with variable angular velocities in different latitudes. For our present purpose it is sufficient to note that the repeated agreement of the two positions of the coronal poles, C computed and C' observed, is rapidly taking the 26.68 day period out of the list of tentative data. Every such coincidence occurring after a large number of revolutions of the sun have intervened renders it very unlikely that chance has given these results, and, according to the theory of probabilities, becomes strong evidence in favor of the truth of the period itself.

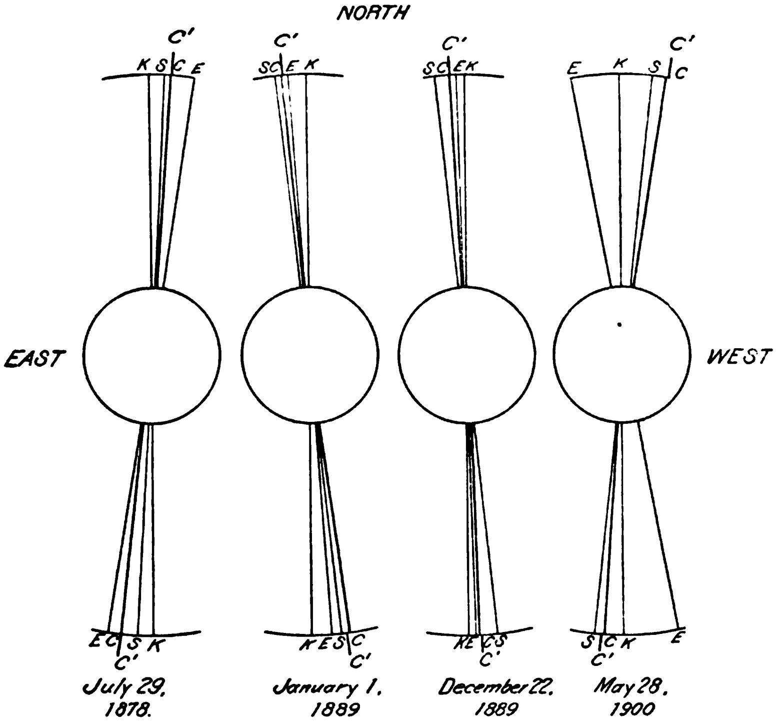

CHART 22.—Computed position of the coronal pole C.
Observed position of the coronal pole C'.

3. THE SUN-SPOT AREAS.

The sun-spot areas, when the available observations were reduced to a homogeneous system, were collected in the 26.68-day period, so that a relative number corresponding to the size of the spotted area on the central meridian of the sun was entered in a tabulation for the interval of time, 1854–1891, with the following result. The two hemispheres were collected separately, and the sums for each day of the period, with their variations on the mean sum, are given in Table 19. These variations are plotted in the second and fourth curves of Chart 23. It was found that similar curves are developed, having the same number of maxima and minima, in the northern and the southern hemispheres, but the curves as a whole, both in general inflection and in the ordering of the crests, are the inverse of each other. This indicates that for some reason the spotted areas on the sun have an excess or a defect, varying from the average in solar longitude, and that some meridians are therefore more prolific than others. This would seem to suggest that a sort of structural nature must exist in the nucleus from whence the spots proceed, such that there is a distinct variation of activity at certain places in longitude. Furthermore, on the same meridians these curves are complementary, which would indicate that the northern and the southern hemispheres, respectively, alternate in activity in the same longitude. This curious result naturally suggests some interaction of positive and negative magnetic and electric forces on the sun, but I can not explain what it is. The variation is vigorous enough to produce residuals as large as 25 or 30 per cent of the average total activity. In accordance with the internal convection of the sun by means of vortices perpendicular to the plane of the equator, it is probable that this alternate formation on successive meridians must be referred to some fundamental law of cooling in large radiating bodies, but this requires investigation.

TABLE 19.—*The sun-spot areas distributed in the 26.68-day period.*

NORTHERN HEMISPHERE.

1854–1891.

	Sum	Variation		Sum	Variation
1	1602	− 49	16	1718	+ 67
2	1373	−278	17	1483	−168
3	1518	−133	18	1937	+286
4	2001	+350	19	1519	−132
5	1581	− 70	20	1384	−267
6	1643	− 8	21	1734	+ 83
7	1729	+ 78	22	1617	− 34
8	2007	+356	23	1561	− 90
9	1617	− 34	24	1826	+175
10	1960	+309	25	1685	+ 34
11	1753	+102	26	1733	+ 82
12	1734	+ 83	27	1526	−125
13	1354	−297	Mean	1651	
14	1187	−464			
15	1794	+143			

SOUTHERN HEMISPHERE.

1854–1891.

	Sum	Variation		Sum	Variation
1	1307	−384	16	1628	− 63
2	1613	− 78	17	1783	+ 92
3	1567	−124	18	1556	−135
4	1865	+174	19	1887	+196
5	1458	−233	20	2017	+326
6	1563	−128	21	1903	+212
7	1887	+196	22	2161	+470
8	1650	− 41	23	1836	+145
9	1175	−516	24	1818	+127
10	1395	−296	25	1645	− 46
11	1145	−546	26	2190	+499
12	1493	−198	27	1308	−383
13	1750	+ 59	Mean	1691	
14	1779	+ 88			
15	2271	+580			

The evidence regarding the formation of sun spots and the allied phenomena is that the sun operates through a series of outbursts, irregular outputs of force, flushes of heat, discharges of magnetic polar force, and intensifications of electric currents in the heated atmosphere. This is apparently inherent in the constitution of the sun, however it may be explained. These curves do not represent fixed and rigid conditions, maxima and minima of permanent potentials arranged in harmonic series of a high order. Also, unless the sun were a homogeneous, smooth, magnetic sphere, symmetrically balanced about its axis, its rotation necessarily would produce variations in the distant magnetic and electric fields of force in contact with it. Prof. A. SCHUSTER, in his paper, "On the possible effects of solar magnetization on the periodic variations of terrestrial magnetism," Phil. Mag., October, 1898, page 395, treats the case of a uniform homogeneously magnetized sphere,

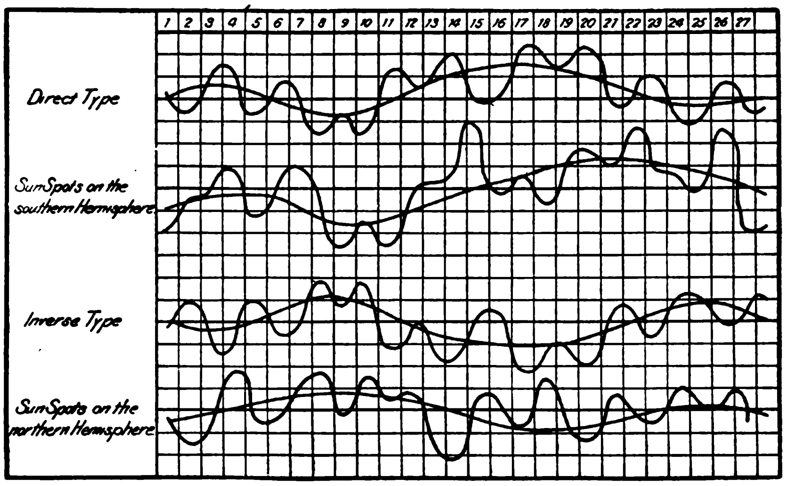

CHART 23.—Comparison of the total sun-spot areas, 1854–1891, with the normal magnetic curve of the 26.68-day period.

and allows for more complicated forms of magnetization by component additions of secondary potentials, but this is always a *steady* distribution. He draws the inference that the existence of a synodic period is excluded, by reason of the relative movement of the earth's axis along the orbit, and also states that the period has no *vera-causa*. But it is evident that the supposition of a fixed potential system is not applicable to the sun, which is essentially a self-active and spasmodic source of energy. The theorems which follow on the assumption of a fixed magnet, rotating in the position of the sun, do not fulfill the actual conditions so as to make the results wholly comparable. The interaction of two permanent spherical fields, as of the sun and the earth, would give certain periodic terms, but the actual sun does not provide these premises. The problem of the effect of a variable system of outbursts in a central sphere has never been solved, and at present the only thing to do is to tabulate the effects without presuppositions as to the result, for the sake of deriving data upon which to found a solution.

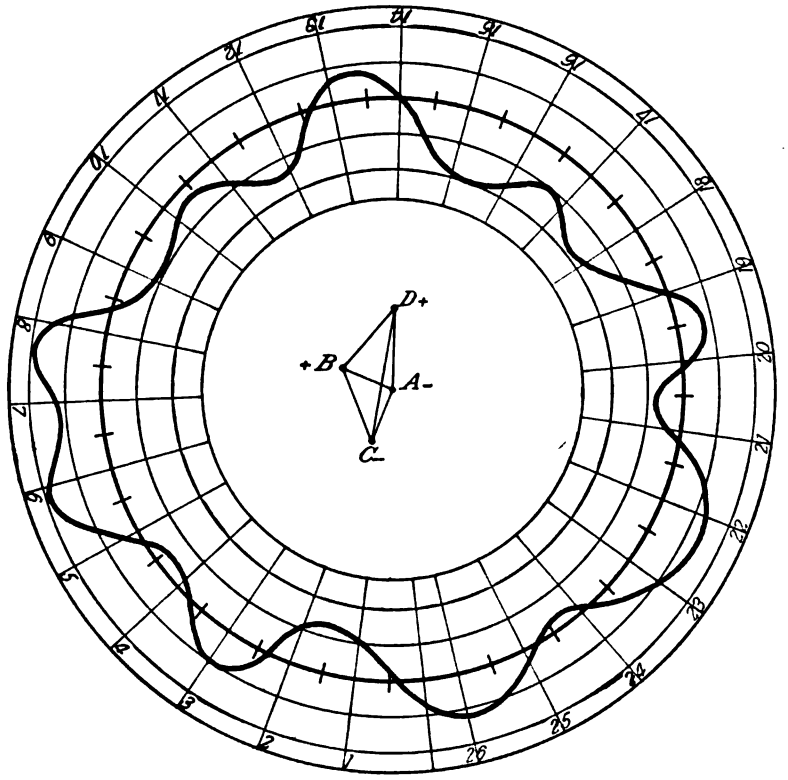

CHART 24.—Direct type of the variation of the magnetic and meteorological elements in the 26.68-day period.
Epoch—June 13.72, 1887. Period 26.67928 days.

With this end in view, I have laboriously arranged the terrestrial magnetic field in the 26.68-day period, and find the curves reproduced in the first and third on Chart 23. The similarity between these terrestrial and solar curves is striking, but the inference has been carefully avoided that the solar distribution of spots is the cause of the terrestrial effects. On the other hand, a different explanation of the cause of this inversion phenomenon in the terrestrial field has been worked out in Bulletin No. 21, and appears to be in accordance with the facts of the case. It may be stated, in passing, that the terrestrial inversion is entirely different from the solar, the latter being a local distribution on the surface of the sun, while the terrestrial is an orbital effect producing semiannual inversions. The type curves have been traced back to 1841 in the terrestrial magnetic field; they reappear in the atmospheric pressures and temperatures of the northwestern portions of the United States with considerable distinctness, and show that the solar activity registers itself not only in the sun's atmosphere, but in that of the earth as well. The northwestern portions of the American Continent are the regions where the cyclones of the northern hemisphere chiefly generate, while the European Continent is the place for their dissipation. This renders the former a specially sensitive place for registering the extra-terrestrial forces; on the other hand, European meteorology deals only with decaying atmospheric structures, and is not adapted to the detection and study of these forces.

(4) THE POLAR ORIGIN OF THE DIRECT TYPE CURVE.

If the direct type of our typical curve be wrapped about a pole as on Chart 24, it produces a certain configuration, which is the effect of having superposed upon a mean magnetic field a series of impulses, assumed to be due to the variable internal magnetization of the sun, which is in turn correlated with changes in pressure, temperature, and electric conductivity in the gases of the solar atmosphere. It is not a stationary curve to be discussed rigidly by the potential theorems. If this curve be examined for centers of activity, by assigning positive and negative poles to proper points, it is found that the curve can be constructed approximately by magnetic interaction from the four points *A B C D*, where the angle *B A C* is equal to 106°. If *A* is the south and *B* the north magnetic pole, then by adding two subordinate poles *C* and *D*, we have *B* and *D* positive, *A* and *C* negative. The Siberian pole in the northern hemisphere and the indistinct Pacific pole in the southern hemisphere of the earth furnish a suggestive analogue, as to the probability of a large magnetized globe possessing minor centers of action in addition to that of the principal axis. Drawing lines extended through the pairs of pole points, and perpendiculars from each pole upon these lines in all simple directions, counting the density of the rays and drawing a proportional intensity curve, we have one quite similar to that of the Chart 24. There is no intention to claim great accuracy for such a construction, yet the conformity of the drawing to the type curve is such as to show that the sun may have four centers of magnetic action. Hence, any theorem based upon a single axis of magnetization is to be regarded as incomplete till this agreement, furnished by the long series of terrestrial magnetic observations already computed, is disposed of in some other way. For these two reasons (1) that the sun does not appear to have a steady magnetization, and (2) that the observations seem to indicate more than a single axis of magnetization, it is proper to withhold assent to the result deduced from the potential theorems, because they ignore these circumstances and are therefore imperfect or inapplicable. If the direct observations produce a synodic period at the earth, and if this period proves to be efficient in terrestrial magnetism and meteorology, as it does, we may utilize it until a complete theory and a full understanding of the physical laws involved are acquired.

Professor SCHUSTER discusses the results of several investigations into the solar rotation and its influence on the earth's magnetism, by means of his theory of "hidden periodicities," using the *declinations* of the Greenwich Observatory for the years 1871–1895.*

Table of results (Schuster).

Period, in days	Intensity or square of amplitude	κ=ratio of the intensity to the expectancy
25. 87	0. 001001	0. 95
25. 929	. 001027	0. 93
26. 68	. 000242	0. 23
25. 809	. 006168	5. 86
25. 825	. 004182	4. 07
26. 181	. 001144	1. 09
26. 255	. 001081	1. 04
26. 814	. 005936	5. 64
27. 061	. 002943	2. 80

It should be observed that "there is a remarkable unanimity in the smallness of the value κ, showing that the amplitudes are even less than the average amplitude calculated on the theory of chance." Also it may be noted that there is about the same probability for the periods 25.809 and 26.814. Of course, both of these can not be simultaneously correct, and either the method of discussion fails or else there must be some explanation of the general failure of any one of this group of periods to conform to the Greenwich observations. The latter is probably the fact. The irregularities in the earth's magnetic field are so great and erratic that it is hardly possible to obtain clear evidence of the true periodic action from any *single* station. It is usually sufficient to take the mean daily values of the components for *five* stations before submitting them to the discussion, but it is not surprising that the records from the Greenwich Declinations alone should have proved insufficient.

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*The periodogram of magnetic declination, as obtained from the records of the Greenwich Observatory during the years 1871–1895. Cambridge Phil. Trans., vol. 18, pp. 107–135, 2 plates.

Furthermore, it is plain that the disturbing vectors in space have three rectangular components referred to the terrestrial magnetic meridians, namely, horizontal or S—N, declination or E—W, and vertical or Nadir-Zenith, and it is therefore an *incomplete procedure to use only one component*, as was done in this discussion. Here it is clearly imperfect, because, as shown by my own computations and by those of VAN BEMMELEN, there is *no true* W—E *component, since the disturbing vectors lie on or very close to the magnetic meridians.* This, of course, refers to the successive means of the 24 hourly observations, or the system of vectors acting from day to day, which eliminates the diurnal variation in longitude. By the theory that the earth lies in an external magnetic field sustained by the sun, the direction of the field at the earth is nearly parallel to the axis of the earth's own field, and there should be no W—E component. The theory and the observations agree that there is no true persistent component which disturbs the declination. Now, Professor SCHUSTER's discussion comes to this same result, and therefore it sustains the theory. Evidently at most his result is merely competent to declare that the E—W component is wanting, but it is not proper to infer from this fact that the horizontal and the vertical components will fail to disclose a solar period, and it can lead to no such conclusion regarding them. Had the discussion been based upon the horizontal or the vertical components or the resultant of them, that being the proper basis for such a work, the result would not be open to this objection.

EKHOLM and ARRHENIUS have sought to find the period of the rotation of the sun by discussing the variations of the aurora* and thunderstorms. Somewhat the same difficulty pertains to this class of material, namely, that it is very discontinuous, and complicated with other transformations in the atmosphere. A single outburst of the auroral intensity will sometimes outweigh the total amount perceived in many days of ordinary activity. It is like trying to discover the period by using the strong magnetic disturbances in place of the continuous traces of the magnetograms. In short, the numerous divergent periods which have been obtained reflect unfavorably either upon the choice of material adopted for discussion, or upon the fact that a mere tabular compilation does not suitably eliminate the other component forces inherent in the crude observations. Thus, thunderstorms are developed only after the solar energy has accumulated and culminated, after drifting eastward in the circulating motion of the lower strata of the atmosphere, and they do not directly measure the time of the solar impulse. In fact, therefore, we infer that the horizontal and vertical magnetic components are more fit to be discussed for a solar period. So many periods are derived having about 26 days in length, that this raises a suspicion that in some way the true solar period is mixed with other components, and that the combination gives such a resultant. From all the data available, one solar rotation takes about 26.7 days at the equator and at the poles, and about 27.3 days in the midst of the sun-spot belt. But it is very difficult to conceive how a period of 26 days—that is, one having a quicker rotation by 1 part in 27—can be derived from the sun in its rotation taken alone by itself. Since thunderstorms and aurora are associated with the materials of the earth's atmosphere, and these drift eastward rapidly over our northern stations, it is evident a component due to the relative drift of the atmosphere over the station of observation must be subtracted from any observed recurrence of events at the station in order to leave the purely solar period. In my opinion this entire subject needs a more careful and thoroughgoing treatment than it has yet received from meteorologists and physicists, and then it is quite likely that many apparent difficulties will take care of themselves and disappear. I desire to state that the phenomenon of inversion which I have described is not accidental, but that it persists in magnetic and meteorological phenomenon. It is quite possible that my explanation of its cause may be imperfect, but that is no argument against the facts adduced in evidence of its existence.

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* Ueber die nahezu-26-tägige Periode der Polarlichter und Gewitter, von Nils Ekholm und Svante Arrhenius.

THE NATURE OF THE CORONAL LIGHT.

We shall now attempt to go a little more closely into the nature of the coronal light. There are three theories before us for consideration: (1) The incandescent theory and dissociation of the elements; (2) the ionization of the solar gases producing as products the electrically charged carriers which are torn from the atoms; and (3) the X-rays as electrical impulses, or pure but minute electromagnetic waves. It is quite probable that the coronal light in reality contains all of these sources of light in mixture, because in the solar atmosphere conditions are favorable for producing each one of them. It is the duty of observers to try to apportion their relative amounts. The coronal light shows a continuous spectrum and polarization, indicating that there are minute solid masses in an incandescent state which also reflect the solar light; there are some fine bright lines present, and some students believe that helium and coronium are the dissociated products of hydrogen. The difficulty with the theory of the reflected or scattered light is that the dark FRAUNHOFER lines corresponding with the light of the photosphere have not been found in the corona. Explanations have been offered of this fact, and special efforts are being made to detect the dark lines in eclipse observations. Much depends upon the result. Furthermore, the previous description of the curvature of the polar and equatorial rays shows that besides the dust particles just mentioned, a large percentage of the total number of rays are composed of electric charges carried upon even finer particles of matter, which are ionized rather than chemical products of dissociation. Also, it may be assumed that the collision of these charged ions with neighboring molecules or molar masses should, by the shock of the impact, detach the. electric charge in the form of electromagnetic impulses, as is possible in accordance with the views explained in the papers by HEAVISIDE, J. J. THOMSON, and others.*

We quote a few sentences from J. J. THOMSON:

> Under the action of the magnetic field the narrow beam of cathode rays spreads out into a broad fan-shaped luminosity in the gas, which is equivalent to a magnetic spectrum. As the cathode rays (1) carry a charge of negative electricity, (2) are deflected by an electrostatic force as if they were negatively electrified, (3) and are acted on by a magnetic force in just the way in which it would act upon a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter. (Phil. Mag., Oct., 1897.)

It is now understood that these particles of matter are very small portions of the ordinary atoms torn apart physically, but not chemically dissociated, by powerful electric discharges. Again,

> If these particles be suddenly stopped, there will, in consequence of electromagnetic induction, be no instantaneous change in the magnetic field; the induction gives rise to a magnetic field which, for a moment, compensates for that destroyed by the stopping of the particle. The new field thus introduced moves off through the dielectric as an electric pulse. When the ratio of the velocity of the moving particle to that of light is nearly unity, two pulses are started when it is stopped: (1) A thin plane sheet, whose thickness is equal to the diameter of the charged particle, and it is propagated in the direction in which the particle is moving; (2) a spherical pulse spreading out in all directions, whose thickness is equal to the diameter of the charged particle, and thus very small compared with the wave length of light. The X-rays are assumed to be these thin pulses of electric and magnetic disturbances which are started when the small negative particles which constitute the cathode rays are stopped. If they are so thin that the time taken by them to pass over a molecule of a substance was small compared with the time of vibration of a molecule, there would be no refraction, and the thinness of the pulse would also account for the absence of diffraction. (Phil. Mag., Feb., 1898.)

The marks of the electromagnetic waves are: Reflexion, rectilinear propagation, polarization, with the magnetic diplacement in the plane of polarization and the electric displacement at right angles to it; refraction, double refraction, interference and diffraction, dispersion, with velocity of propagation dependent upon the inductivity and permeability of the medium. Those of the X-rays are: Apparent absence of regular reflexion and polarization, of refraction and diffraction, and of dispersion; the velocities are less than those of light; they are probably electromagnetic pulses, and not longitudinal or transverse waves of short length; they cause all bodies, whether conductors or dielectrics, to be conductors of electricity; they discharge electrified bodies, those which are opaque rapidly, and those which are transparent slowly; they are transmitted through bodies having carbon, hydrogen, and oxygen elements, while these absorb heat; they form secondary types of radiation when they strike on fluorescent and other radio-active bodies; they increase the number of nuclei in the formation of cloudy condensation; they are not found in ordinary sunlight; they appear mixed with cathode rays in a vacuum tube. But especially the X-rays differ from electromagnetic waves in that they possess a much greater power of penetrating opaque bodies, *and in that they can not be deflected by a magnet.* The same is true regarding their relation to the cathode rays, which penetrate opaque bodies only slightly, and can be deflected by a magnet. **Roiti** asserts that the X-rays are mixed with cathode rays, but can not be separated by simple subtraction, rather by the deflection of a magnetic field. **Trowbridge** finds that X-rays are produced at all points of a continuous conductor inclosed in a vacuum tube where a steady, not oscillating discharge, current of very high pressure through a large resistance is maintained in it. He infers that the X-ray phenomena, produced by a steady battery current, *strongly suggest an electrical theory of the origin of the sun's corona.* (Phil. Mag., July & Sept., 1900.)

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*J. J. Thomson, Phil. Mag., July, 1889; O. Heaviside, Phil. Mag. (5), XXXIX, 1889; W. B. Morton, Phil. Mag., June, 1896; J. J. Thomson, Phil. Mag., Feb., 1898.

We remark in this connection that the coronal streamers seem to have more properties in common with the cathode-type of radiation than either of the others. If the phenomenon, above mentioned, of deflection of the rays and the clearing of the sun's polar region of them is admitted, it is decisive against the X-ray theory, and against the electro-magnetic dissociation theory, because neither of these provide for deflection of the rays in a magnetic field. There may be some admixture of these three types of rays, and, if so, careful observation of the corona may apportion the several kinds, because the cathode or ionized rays would often be crossed by the nondeflected rays of the other radiations.

Mr. **Abbot's** report on the Smithsonian expedition's observations at Wadesboro, N. C., on the eclipse of May 28, 1900 (Astro. Phys., July, 1900), gives the following results:

1. The coronal radiation was recognized by the bolometer, and gave at least 5 millimeters deflection over that of the dark moon.
2. The radiation reflected by the earth's atmosphere during the partial phase is vastly more intense than that of the corona.
3. The corona is effectively cooler than the bolometer, and appears, therefore, neither to reflect much light from the sun, nor, chiefly by virtue of a high temperature, to give light of its own, but seems rather to be giving light in a manner not associated with a high temperature, or at least with the preponderance of infra-red rays usual in the spectrum of hot bodies. This involves a rejection of both the eruptive and the meteoric coronal theories. If an investigation of glow electrical discharges in high vacua should be found to yield effects approximating those of the corona, it would seem plausible to adopt this explanation of the coronal light.

The foregoing statement by the Smithsonian observers is readily perceived to be in accord with the views set forth in the preceding pages. If the coronal light consists of electrically charged particles produced by ionization then we may make further inferences. The light is due to the electrical envelope of the atom, which is in vibration, and the heat to the oscillations of the material particles present. The electrical charges seem to reach a definite minimum of inertia, the same that the charges have on electrolytic ions, while the material portions are only one-thousandth part the size of the common atoms; the material substance may even be wholly missing, according to J. J. **Thompson's** idea of discerptible atoms, or **Lamor's** view of disembodied electrons. Hence the light energy is largely retained, while the heat energy is diminished indefinitely, thus agreeing with the fact that the infra-red heat rays are largely diminished in the coronal light. Therefore the incandescent particles in the corona must be very small, or else they must be few in number in the unit volume. **Campbell** found in the Indian eclipse of 1898 that the inner coronal light gives a continuous spectrum with total absence of dark lines. Such facts as these strengthen the view that the coronal radiation is much like the cathode rays of a vacuum tube. Of course the corollary follows that the atmosphere of the sun is the seat of powerful electric discharge currents, and hence that the induction from these and other sources of electricity causes variations in the magnetization of the sun itself, so that the assumption of a fixed magnetization can not be adopted in analytic discussions, without making due allowance for this fact.

THE ZEEMAN EFFECT.

Zeeman remarks in his paper "On the influence of magnetism on the nature of light emitted by a substance" (Phil. Mag., March, 1896):

> It seems very promising to investigate the motion of the ions for various substances, under varying circumstances of temperature and pressure, with varying intensities of magnetization. Further inquiry must also decide as to how far the strong magnetic field, existing, according to some, at the surface of the sun, may change its spectrum.

The **Zeeman** effect has been studied experimentally, and explained theoretically by **Lamor**, **Michelson**, **Cornu**, **Preston**, **Lorentz**, **Voigt**, **Reese**, and others, so that the phenomenon is well understood. (Compare Table 40.) The spectrum line, viewed along a strong magnetic field, is transformed into a doublet on the edge of the widened line, both rays being circularly polarized, while a middle oscillation is invisible because it takes place in the line of sight which is the direction of the lines of force. If viewed across the magnetic field a triplet is seen, the outer lines being plane polarized parallel to the field and the middle line at right angles to it. These lines can be alternately cut out by turning a **Nichol**'s prism parallel or at right angles to the lines of the magnetic field, respectively. It has been found by investigation that the phenomenon in some lines is much more complicated, producing quadruplets and even much higher orders of separation and subdivision. In general the effect has been analytically explained by equations of motion, which assume that the motion of the ion producing the radiations is in an orbit, circular, elliptical, or more complex, and is under a force of attraction drawing the mass of the ion to the center of the molecular system, and also a force of rotation impelling it round the axis of the magnetic line. Since light radiation is made up of ether motions produced by ions rotating in all possible planes and directions, the magnetic field simply assorts or resolves them into right and left hand rotations in planes perpendicular to its lines of force, and into harmonic linear oscillations along its lines. The superposition of the curl motions of the magnetic field upon these motions of the ions accelerates or retards the periods, and then the spectrum grating assorts the resulting vibrations into lines displaced by a certain $\Delta\lambda$ from the original position of λ.

The important points for our present purpose are the facts, that (1) in the ions of gas the charges of electricity are the same as those which occur in the electrolysis of liquids, while the mass of the carriers in gaseous ions is a small fraction, one-thousandth of those in liquids. The evidence points strongly to the disruption of the atomic mass, though it seems incredible to the imagination, but even so our interest is especially concentrated upon the orbital motion of the electric charge and its effects when propagated in electro-magnetic waves of light. The alternate hypothesis to account for the facts is that the ion is a disembodied unit of electricity, called an electron, constant in inertia and able to exist distinct from the ether and from matter itself. This will be a subject of scientific discussion for some time to come, and it involves points of fundamental theoretical importance. (2) The magnetic line of force is shown to be a rotation of the ether about the axis of the line, and it is therefore a vortex in the ether, able to enter into combination with the orbital motions of the ions producing light. (3) This orbital rotation of distinct charges of electricity about the mass of the atom, like a close satellite about its planet, is capable of transforming an atom into a magnet. Professor **Fitzgerald** remarks:

> The ion revolving in its orbit is equivalent to an electric current round the orbit, and therefore the revolving ion and the matter with which it is associated behave as a little magnet having its axis perpendicular to the plane of the orbit.'

The subject of electrical charges moving in circular orbits has been worked out by **Heaviside**, J. J. **Thomson**, **Schuster**, and others, so that the subordinate theoretical relations are well known. (Compare Table 37.) **Reese** (Astro. Phys., Sept., 1900) objects that this rotation of an isolated charge is not equivalent to an electric current, on account of the discontinuity in its electro-magnetic impulses. But it is so practically if the frequency amounts to many million rotations per second, and unless the disturbances of the ether by induction do not subside instantly. Furthermore, there has been much discussion regarding the form of the equations to be used in accounting for the complicated forms of the **Zeeman** effect, as shown by the papers mentioned, and **Preston** has even introduced precessional periodic rotations of the plane of the elliptical orbit, a periodic motion of the orbit about the line of apses, and also a periodic motion of the angle of inclination. (Compare Table 39.) This is indeed introducing us into molecular astronomy, with all of its complex perturbations. It seems to me that he is correct in assuming that in addition to the attraction to the center of the mass of the molecule, there should be a mutual attraction between the several atomic constituents of the molecule, as between the planets of a solar system, and that these complex forms of the **Zeeman** lines which are observed must be analyzed on the general principle of celestial astronomy, although the orbits perturbed are of the most minute dimensions.

MAGNETIZATION IN THE SOLAR AND TERRESTRIAL ATMOSPHERES THROUGH IONIZATION.

We obtain an important principle of physics for the interpretation of solar and terrestrial meteorology if we assume that at the source of the light radiations in the sun the atoms must be practically electro-magnets; it is when the electric discharge currents transform the ordinary chemical atoms by ionization into atomic magnets that they are in a condition to emit electro-magnetic radiations through the interplanetary spaces. When this radiation falls upon the earth's atmosphere, a state of ionization is also set up in its atoms, especially in the daytime and throughout the entire depth of it, which converts these atoms into magnets as long as the ionization continues. **Elster** and **Geitel** have already indicated to what a remarkable extent the phenomena of atmospheric electricity are harmonized by the theory of ionization, attributed chiefly to the action of the ultra violet rays. This transitory state of magnetization *in situ*, produced by the electric currents of charged ions is apparently one of the important missing links in our understanding of the system of the physical causes and effects at work in nature.

It will be remembered that in my discussion of the vector system of magnetic deflecting forces operating to produce the diurnal variations of the terrestrial magnetic field, I attributed them not to any system of electric currents operating in the earth's atmosphere, but to a magnetic effect produced by the electro-magnetic field itself. It is true that I had no conception of the phenomenon of ionization when my paper was written, as indeed the subject has been wholly elucidated since that time, and therefore my language was incomplete; but nevertheless it is easily seen that I approached very closely to the seat of the physical process involved. I said:

> The diurnal vector system depends exclusively upon the sun's electro-magnetic or sunlight field, which is a radial field, and apparently induces in the ether an efficient polarization in respect to exploring magnets on the surface of the earth. (Bulletin No. 21, p. 17.)
>
> The immense rapidity of the vibrations of light in the case of a train of waves from the source to the observer practically integrates the system into a type of polarized ether. (p. 34)
>
> The electro-magnetic theory of light implies the existence of a magnetic field practically uniform in force and direction relatively to any magnet large in comparison with the wave length of light, and hence to any magnetic except of atomic and molecular dimensions. (p. 81.)

This was clearly a very close approximation to the more correct statement that the sunlight or electro-magnetic radiations produce ionization in the earth's atmosphere, and that this is accompanied by a subordinate magnetic effect on the individual atoms. In the International Cloud Report, in discussing the diurnal variations of the barometer, after showing the close relations between the diurnal magnetic vectors and the diurnal components of the motions of the atmosphere, and having disapproved the "thermic-manometric process theory" and also the "gravitational tide theory," it is said, the phenomenon is due to the "magnetic attraction" of a field having a certain configuration, depending upon the electro-magnetic radiation (p. 476). This excluded the common theory of electric currents in the atmosphere, the pressure, and the temperature variation theories, and in effect adopted the *ionization-magnetic theory.* We shall return to this topic and discuss it more fully in another connection.

THE EFFECT OF PRESSURE ON LIGHT.

The ZEEMAN effect changes the wave lengths of light by the action of a magnetic field, and the pressure effect shifts the spectrum lines by means of a change in the pressure of the surrounding medium. (Compare Table 40.) The change of period of vibration of luminous molecules or atoms by these two methods should be distinguished from the change of waves which have been emitted through refraction and through the rotation of the plane of polarization in a magnetic field, which is the same as a change in the velocity of propagation of light waves. It is also necessary to bear in mind that there are two theories employed for the explanation of these phenomena, the rivals of one another for the honor of scientific sanction and final adoption, namely, the dynamic and the electromagnetic theories. The former attributes the change of periodic vibration and shifting of the waves in the spectrum to a damping or acceleration of the original periods in which the atoms or molecules as individual masses are moving; the latter to a similar change in the periods of the electrical charges which the atoms carry, rather than to the carrying masses themselves. The ZEEMAN effect seems to be more favorable to the electromagnetic view, and the pressure effect to the dynamic view. Some go so far in ascribing radiation to the vibrations of the electric charges as to subordinate the material mass even to the vanishing point, and thus make the electron the primary thing from which matter is itself constructed; others find in the vibrations of the atomic masses and in the collisions of the molecules sufficient ground for a complete explanation of the facts without any resort to disembodied electrons. These rival schools of thought will no doubt discuss for some time to come the various arguments for and against the adoption of either of these radically different fundamental conceptions. The pressure effect is briefly summarized as follows: A shift in the position of a spectrum line has been found by the experiments of JEWELL, HUMPHREYS, MOHLER, WILSON, and WILSING, to occur, such that it is proportional to the wave length, the difference of pressure, the coefficient of linear expansion of the substance in its solid state, the cube root of the atomic volume, and inversely proportional to the absolute temperature of the melting point; also that there is a proportionality between the principal series and the first and second subordinate series of a group. Hence the shift varies from one element to another, but is not far from 0.010 ÅNGOTRÖM unit per atmosphere, the range extending from very low pressures up to twenty atmospheres by actual experiment. The change in pressure also broadens some lines, either symmetrically or unsymmetrically; it brings out the reversals clearly, but the chief effect in the increase of pressure of the medium, as for example, of air surrounding the electric arc in which the element is rendered incandescent, is to displace or shift the place of the line in the spectrum toward the red end having slower periods. An increase in the temperature increases the number and the intensity of the lines, but does not appreciably shift the lines; an increase in the density or amount of material present in the unit volume increases the width of the lines, either symmetrically or more on one side than the other, but does not seem to shift the lines. A broad line in the solar spectrum is therefore due to the emission of the same element distributed through a great range in elevation in the sun's atmosphere, where the pressure changes considerably. The observed shift of the solar relative to the terrestrial lines indicates that the pressure in the solar reversing layer at the bottom of the chromosphere is about five or six atmospheres, and that it is small near the top of the chromosphere. Irregularities in a line are due chiefly to motions in the line of sight, as distinguished from lines broadened through a wide range of pressure or very variable distributions of the material density. Fine sharp lines tend to be produced nearer the top of the solar atmosphere, and hence, by selecting lines which are emitted at different altitudes, studies can be made upon the relative angular velocities of the different strata, as has been done by DUNER and CREW, though this subject is still incomplete. Since the wave lengths and corresponding positions of lines are related to these several functions it is not possible to determine absolute standards of wave lengths, as MICHELSON proposed to do, unless the conditions of normal waves are definitely prescribed.

It has been shown by v. LOMMEL that a shift of spectrum line is due to change in the wave length, produced by damping the period through superposing an excitant period upon it. His theory depends solely upon the resistance of the medium to the motion of the vibrating atoms.

but **Wilsing** shows that this damping coefficient and the other dependent terms must be modified so as to include a change in inertia due to the internal friction of the medium upon itself. This theory was first applied by **Bessel** to pendulum vibrations, and was confirmed theoretically by **Stokes**. **Godfrey** points out that the acoustic vibrations of a plate were accounted for by **Rayleigh**, by superposing a similar subordinate term upon the simple effect of emission of radiation. Also there is an electrical analogue which requires the same kind of treatment. The most important conclusion to be drawn from these facts is that no dissociation hypothesis regarding solar elements is required, but that all the peculiar features in the spectrum lines can be explained by variations of pressure in the sun's atmosphere with the elevation, motion in the line of sight, and changes in the temperature and density of the material. Hence the uprushes and downrushes in the sun's atmosphere, and the motions in the line of sight can all be studied in the spectral lines, as well as the distribution of heat and the materials of the elements, so that finally a quantitative and qualitative scientific knowledge of the sun's constituents will be acquired, and that, too, without resorting to any hypothesis implying unusual or improbable conditions.

THE MAGNETIZATION AND TEMPERATURE OF THE SUN.

The fact that the sun is at a very high temperature seems to many physicists a sufficient reason for concluding that it is not a magnetic sphere. The analogue usually referred to is that of a steel magnet which loses its magnetization when the temperature is raised considerably. On the other hand, the state of the earth would appear to be a more correct analogue, and it is evident that although the interior temperature is excessively high, it yet sustains a magnetic field. The attempt to account for such terrestrial magnetism as exists, through the electro-magnetic induction of currents of electricity in the upper atmosphere, when examined breaks down through the insufficiency of the possible causes of such currents, and the fact that the air is a powerful nonconductor, like the ether, under ordinary conditions, and hence that electric currents are excluded except in very limited regions and under very restricted conditions. There are three possible kinds of electric currents in the atmosphere: (1) The displacement currents due to the readjustment of static potentials of electricity, which in the atmosphere is localized and held apart by pressures up to many millions of volts; (2) the convection currents which may occur by the transportation of electric charges in the movements of the wind circulation, and in the motions of the ions which are produced in special places; and (3) in the conduction currents which occasionally occur, as in lightning flashes when the pressure discharges breaks down the air as a dielectric and temporarily makes it an efficient conductor. **Trowbridge** (Phil. Mag., August, 1898) finds that the "initial resistance of the air steadily diminishes with the powerful electric stresses, and under disruptive discharge sinks to 2 or 3 ohms." He infers that **Edlund's** idea of the ether as a conductor of electricity may be true under the conditions where several million volts operate to break it down. (Phil. Mag., May, 1897.) J. J. **Thomson** in his Recent Researches contends that **Edlund's** view is disproven on the ground that a vacuum would be opaque, and that no light would be transmitted from the stars through interstellar space. (p. 98.) **Sutherland** (Phil. Mag., March, 1899) seeks to reconcile this difference of opinion by saying that under moderate electrical pressures the ether and the air are nonconductors, but that under very high pressures with oscillating discharge they may become good conductors, and that this is due to the dissociation of the neutral molecules, atoms, or even electrons, into positive and negative parts, which by ionization produces temporary conductivity. That is to say, in the path of the lightning flash there is intense ionization and corresponding conductivity. This, however, is merely calling by the name conductivity that process which really belongs to the case of convectivity, if the dissociation and ionization theory is realized. Likewise on the sun there must be similar and numerous circumstances producing such temporary conductivity, though on the earth it is confined to few and very transient actions in the lower atmosphere. If this is the case regarding the absence of electrical conductivity in the relatively high barometric pressures and high densities that prevail in the lower parts of the atmosphere, it is found that conductivity also takes place very readily in rarefied gases and at very low pressures. When the pressure is reduced as low as 1 millimeter, more or less, and the molecules are comparatively far apart from each other, it is a common experiment to find that the conductivity is very good when ionization is produced in any way. If the pressure of a gas is reduced gradually to a vacuum, it is found that at a certain minimum pressure the conductivity is a maximum, but that the conductivity decreases rapidly as the pressure is further decreased. This indicates that a given density of the molecules is better for conductivity than a pure vacuum. It is also an argument against the conductivity of pure ether. Hence we infer that only a very thin stratum of air, where the pressure of the atmosphere is about 1 millimeter, is suitable for electrical conductivity, and I do not believe that the magnetic state of the earth is produced by electric currents flowing in this thin stratum.

There are, however, other ways of producing ionization than through the action of the electric discharge current. Thus a gas is rendered more or less conductive (1) by the passage of RÖNTGEN rays through it; (2) by the passage of Uranium and Thorium rays through it; (3) in the neighborhood of a piece of metal heated to redness; (4) near a flame; (5) near an electric arc or spark discharge; (6) near a piece of metal illuminated by ultra violet rays; and generally (7) the passage of solar radiation through the earth's atmosphere or through the sun's atmosphere is believed to be attended by ionization. In all cases the resulting change in conductivity is due to the motion of the ions present. The negative ions move on the average one and one-fourth times as fast as the positive ions, so that if produced simultaneously they tend to separate into positive and negative groups. From this results the increase of potential difference that precedes the lightning flash, followed by a readjustment of the electricity toward equilibrium. It is to be particularly observed that the state of ionization in the atmosphere is set up only in limited spaces, or in small quantities, and that the general statement still holds true that the air is a powerful dielectric and a poor conductor of electricity. The most careful experiments show that air is incapable of receiving a charge of electricity (J. J. THOMSON, Phil. Mag., April, 1890), and that the apparent exceptions are due to the presence of dust or to the appearance of ions. When Lord KELVIN and MAGNUS MACLEAN state (Phil. Mag., August, 1894) that air can be electrified either positively or negatively, because an isolated spherule of pure water electrified either positively or negatively can be wholly evaporated, it is evident that they mean to speak of the fine mixture of aqueous vapor bearing electric charges with dry air in the unsaturated stage, and are not wholly explicit, but they really refer to a type of ionization. We believe that it is quantitatively proven that the air is a nonconductor to currents of electricity traversing large regions of the earth, such as would be necessary to produce the magnetic forces involved in terrestrial magnetism, and that all the theories based upon the assumed conductivity of the air are untenable.

Having examined the conductivity prevailing in cold gases, such as the earth's atmosphere, we may return to the sun, whose atmosphere is very hot, and in consequence favorable to an abundant, if not excessive, ionization, and therefore becomes equivalent practically to a metallic type of conductivity. The physical state of such an atmosphere is very complex, having great kinetic molecular energy or heat, through collisions of high frequency, an abundant development of ionized atoms from the motion of whose electric charges the electromagnetic waves of radiation spread into space, very numerous isolated cathodic charges of electricity subject to deflection in a magnetic field. It is assumed that heat is energy of vibration in the molecular portions of matter; that electromagnetic radiation is an oscillation of the surface electric charges; and that cathode rays are a subordinate type of radiation of charged particles, while the RÖNTGEN, Uranium, Thorium rays, fluorescences, and the still further subordinate radio-active radiations, represent other forms of motion pertaining to the delicate connections existing between the ether and matter. When radiation of any type strikes upon the earth's atmosphere, the most complex phenomena result. This energy is taken up in corresponding molecular motions as heat, or in the ionization of atoms, or in the formation of the more strictly electrostatic charges, or finally in setting up similar subordinate radiations. It seems necessary to distinguish two forms of ionization: (1) That in which the electric charge of the ion circulates in a kind of orbit about the atom and thus converts it into a minute magnet, and (2) the more isolated charges, as in cathodic rays where the light waves are less developed and the motion of the charge is aperiodic, or even anomalous. The photospheric radiation of the sun would seem to be partly of the former type, since its rays appear to be quite subject to magnetic deflection, and partly of the latter type, since there are other coronal streamers extending to enormous distances in space with very little curvature.

One of the leading difficulties in scientific analysis is to distinguish between mathematical fictions and physical realities. There have been numerous instances of the mistaken use of correct mathematical propositions for the explanation of physical phenomena, and this is especially the case before it becomes possible to collect the observations and verify the facts which critically test the theory employed. Because a mathematical theorem might theoretically be applicable to certain conditions in physics, it is unfortunately by no means a proof that this is the true analysis. The history of science indicates how many mathematical fictions have been rejected by the development of better observational data. For example, a spherical magnet having the well-known lines of force surrounding it, may be conceived to be developed (1) by placing a small magnet at the center, (2) by placing two isolated poles near the center, (3) by filling the interior with uniformly magnetized material polarized in one direction, (4) by placing layers of positive and negative magnetism on the surface and distributing it according to the cosine law, (5) by a suitable electric-current system circulating on the surface, (6) by induction from an external magnet, (7) by putting the sphere in an external magnetic field whose sources are distant. Yet, it is necessary to distinguish the facts carefully before, for example, attributing the earth's magnetism to any of these possible causes. In the same way, the magnetism of large masses of matter has been attributed to three different theories: (1) The Weber-Ewing theory, which assumes that each molecule is a small permanent magnet of itself, and that the magnetization is an act of setting all the molecular axes to point one way, which is the polarization of the molecules; (2) the Amperè electric-current theory, which considers that each atom or molecule is surrounded by permanent currents circulating in opposite directions on the two hemispheres, and that they are thus polarized; (3) the Rosing theory (Phil. Mag., Sept., 1896), that matter when magnetized is put into the same motion as the surrounding magnetic field. The connection between ether motion and matter in motion is still obscure, but many physicists have attributed the magnetism of the sun and the earth to their rotation in the ether medium. J. J. Thomson concludes a discussion of this topic (Phil. Mag., April, 1894) by saying:

> It would appear that if the atoms possess this specific attraction for the two electricities, a large rotating body ought to produce a magnetic field.

Lord Kelvin discusses the action of an "atom" acting on the ether within and around it, according to the idea of attraction and repulsion (Phil. Mag., Aug. and Sept., 1900), and approaches a one-fluid theory of electricity, but identifies the electric fluid with the ether as an elastic solid pervading all space. He says:

> Stress in ether being freed from the impossible task of transmitting both electrostatic and magnetic force is quite competent to perform the simpler duties of transmitting magnetic force alone. If we assume the density of the ether as much as 10^{-6}, I am content at present, however, to suggest 10^{-9}, this, with the velocity of light 300,000 kilometers per second, makes the rigidity (being density times velocity squared) equal to 9×10^{11} dynes per square centimeter, which is somewhat greater than the rigidity of steel, 7×10^{11}. It is clearly not for want of strength that we need question the competence of ether to transmit magnetic force.

This conclusion comes from discussing the motion of an atom through the ether, and shows that the transmission of magnetic force is the immediate result—that is to say, a transmission of velocity of rotation or a magnetic field of force. When the atoms are associated in a large revolving body, similar actions upon the ether set up a magnetic field or polarization throughout the entire mass. The magnetic induction is a kind of motion of ether communicated to matter, and Rosing explains the phenomenon of magnetization as simply a reflexion of tubes of induction from matter. Whatever may be the exact nature of this connection the opinions are certainly gaining ground (1) that the ether is capable of magnetizing a body rotating in it; (2) that the ether is incapable of transmitting electrostatic and magnetic force simultaneously, but is better suited to transmit magnetic force than electrostatic, having less work to do in that type of transmission of energy.

The temperature of a body such as the sun does not primarily enter into this question. Heat is caused by a disorganized motion of molecules in collision, and is a vibration of the substance of matter; electric currents and magnetic rotations, polarized or not, may go on quite independently of such heat operations; if the entire body rotates in the ether, polarizing forces may be generated such as to organize the molecules, so that while executing heat collisions they shall individually hold their magnetic axes parallel to an axis of polarization. It is quite likely that all molecules of matter are magnetic; heat may in many instances disorganize the polarization so that a given mass of the molecules may not appear to be magnetic, but this is not a necessity; and in fact the sun and the earth seem to possess such magnetizations, resulting from their rotations, as to warrant us in assuming that it is not so in their cases. The enormous pressures reducing the matter to viscous density may be also an associate cause tending to facilitate such polarization of the sun. At any rate, enough has been said to show that one has a fair working hypothesis in assuming that the sun is a strong magnetic body, that it is not uniformly magnetized, and that hence a *vera causa* does exist for propagating the variations of its magnetic forces at a great distance from it.

We have thus two true causes for the magnetization of the sun—(1) the convectional vortices of radiation in the interior, and (2) the rotation of the entire mass in the surrounding ether. Both causes no doubt work together and efficiently supplement each other.

THE TRANSMISSION OF ENERGY FROM THE SUN TO THE EARTH.

The evidence from observations on the conductivity of the ether is that it is nonconducting of itself, except when broken down by a powerful electric discharge, or when ionized bodies or other conducting materials are scattered through it. There may be a very minute increase of conductivity in the immediate neighborhood of the sun, but generally the ether is a perfect insulator between the sun and the earth. This point is of importance because of the tendency among physicists to treat cosmical magnetic problems as if the ether were a conducting medium, and the rotation of a body in it were sufficient to induce a system of electric currents of characteristic form. SCHUSTER has shown (Terrest. Mag., Jan., 1896) that any such possible conductivity must be very small, because otherwise the earth's axes of magnetism and rotation would tend to coincide, and the length of the day would be changed by an amount sufficient for the extant astronomical observations to detect. Any conductivity to be derived from interplanetary meteoric matter must evidently be too weak for practical consideration, because of the excessively wide spacial separation between the material portions.

The transmission of energy between the sun and the earth is confined to three possible methods, (1) the electromagnetic radiation, but not including the RÖNTGEN radiation, which does not exist in the sunlight; (2) the electrostatic rays stretching from the sun to the earth in radial lines; (3) the magnetic polar rays which reach the earth along oval paths and depend upon the magnetization of the sun. The electromagnetic radiation, on entering the atmosphere, may cause a small amount of conductivity throughout the atmosphere by the generation of ions, and it is the mode by which most of the energy actually comes from the sun; the ether is a medium which transmits electrostatic stress only at the expense of a very large amount of work, and the potential between the sun and the earth must be enormous beyond any probability to make an effect perceptible at the earth, and we do not believe that it exists; the magnetic polar field readily transmits energy of a certain kind on account of the susceptibility of the ether to take on vortical rotations, though limited to static forms except during temporary adjustments. We will now give our attention to this magnetic field and the testimony of the observations regarding its effects.

As already stated, some students have found in this field an explanation of the remarkable synchronism between the solar and the terrestrial phenomena, as shown in the 11-year solar period and the 27-day period, which has been detected generally in the terrestrial magnetic field and in the several meteorological elements. Lord KELVIN, in his presidential address before the British Association for the Advancement of Science (Nature, December 1, 1892), gave the result of his computation on the work done by the sun in producing a given magnetic storm, and states its amount to be excessive, as follows:

> Thus, in this eight hours of a not very severe magnetic storm, as much work must have been done by the sun in sending magnetic waves out in all directions through space as he actually does in four months of his regular heat and light. This result, it seems to me, is absolutely conclusive against the supposition that terrestrial magnetic storms are due to magnetic action of the sun; or to any kind of dynamical action taking place within the sun, or in connection with hurricanes in his atmosphere, or anywhere near the sun outside. It seems as if we may also be forced to conclude that the supposed connection between magnetic storms and sun spots is unreal, and that the seeming agreement between the periods has been a mere coincidence.

This theory consists in substituting in the equation of energy, $E=-\frac{1}{8\pi}\int\int V\frac{dV}{dn}dS$, the values $V=\frac{m\cos\theta}{R^2}$, and $H=\frac{m}{r_3}$, so that $E=\frac{H^2}{3}\cdot\frac{r^6}{R^3}$, where $H=0.001$ C. G. S., the magnetic force as observed to vary at the earth, R the solar diameter and r the distance from the sun to the earth. Hence $E=13\times10^{39}$, and the rate of doing work for 50 minutes is 43×10^{36}. (This solution was communicated to me by Professor SCHUSTER.) This theorem and example have been widely quoted, and have carried much weight with them, so that they have acted as a barrier against further investigations on the direct magnetic field of the sun, if not as conclusive evidence against its existence. But before any general theorem of the kind can be accepted it must be shown to be in conformity with the body of observed facts known to prevail in this connection; it should also be shown to exclude all other sources of influence upon the terrestrial magnetic disturbances. Thus it may possibly prove to be the case that there are variations in the quality and even the quantity of the solar radiation, and that the action of this differential source of energy in the ether waves reacts upon the state of the constituents of the atmosphere in the upper regions, and thence to the magnetic field, so that it would not be correct to attribute all the disturbance effect to direct polar magnetism alone. The delicate atomic changes which have been detected in molecular physics make this line of argument not only permissible but also essential. The polar magnetic field working in conjunction with the ionization effects of the electromagnetic field may magnify the magnetic perturbations from some comparatively small quantity to those relatively large values observed during intense magnetic storms, and at the times of the auroral displays. If, as is probable, the aurora is the florescent effect in the argon constituent of the atmosphere, generated by the electric brush discharge following the lines of the magnetic field of the earth, then the superposition upon this effect of the true magnetic solar field may increase the disturbance of the terrestrial magnetic field considerably throughout the strata of the atmosphere. Indeed, we shall indicate that some such atomic action is apparently involved in the production of the diurnal variations of the earth's magnetic field, and that the long-sought cause of this phenomenon will be found in this principle, rather than in the electromagnetic effects of any hypothetical system of electrical currents flowing in the cirrus strata.

But it is not in the incomplete knowledge involved in these conjectural inferences from partially understood physical operations existing in the earth's atmosphere that the real difficulty exists in the way of accepting Lord KELVIN's conclusion. That sort of probable evidence will not become positive till the variability of the solar radiation is established and its complete effect upon the atmospheric ionization fully worked out. The chief obstacle consists in the fact that the view is opposed by an enormous amount of direct observational evidence, persistently accumulating over a long range of time, in all parts of the world, as expressed in the geometrical coordinates of the vectors of the deflecting magnetic forces which are superposed upon the normal terrestrial magnetic field. These results of observation are so well known that very few scientists deny that such synchronism between the solar activity and the terrestrial effect really exists, though there is still difference of opinion as to the way in which this connection between the sun and the earth takes place. As already stated, the primary trouble with assigning to the sun a strong magnetic field has been its high temperature, but, as we have seen, there are decisive evidences of such solar magnetic influence in the lines of the solar corona. The second difficulty has been the amount of the magnetization required to produce the terrestrial effects, but this may be removed by a further study of the effects of the ionized atoms acting upon the magnetic lines which pass through the atmosphere. Finally, as already indicated in the convectional vortex radiation in the interior of the sun, a single vortex tube if located near the axis of rotation may produce a given line of magnetic force outside the sun which can penetrate to the earth. Hence, we need not assume that the entire body of the sun is involved simultaneously in these temporary outbreaks of magnetic force, so that the observed force at any point in space may vary not a little for a while from the mean value of a uniformly magnetized sphere in the place of the sun itself. Thus we can look for disturbances at the earth which do not necessarily involve the entire interplanetary space surrounding the sun up to the same maximum. As confirmatory of the direct magnetic theory we have the following lines of argument, which are here very briefly summarized, but which could be greatly extended in view of the large amount of reliable material derived from the observations already in our possession:

SYNCHRONISM BETWEEN THE SOLAR SURFACE VARIATIONS, THE CHANGES IN THE TERRESTRIAL MAGNETIC FIELD AND THE METEOROLOGICAL ELEMENTS.

(1) In a paper by **William Ellis**, F. R. S., "On the relation between the diurnal range of magnetic declination and horizontal force and the period of solar spot frequency," in the proceedings of the Royal Society, Volume 63, is given Chart 25, drawn by him from his discussion of the data for the interval 1841 to 1896, inclusive. He says regarding the result:

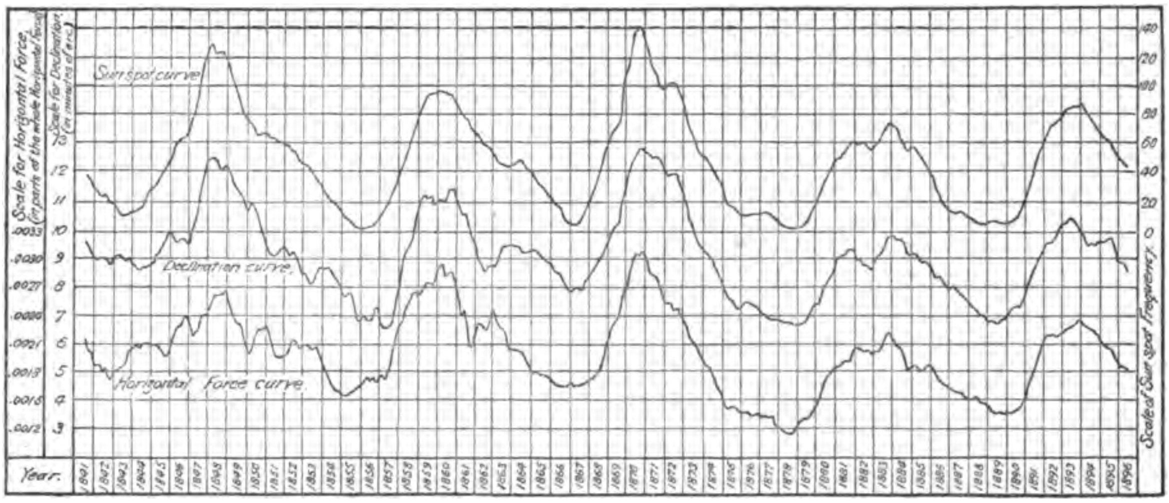


Chart 25.—Smoothed curves of sun spot frequency (Wolf) compared with corresponding curves showing the variation in diurnal range of the magnetic elements of declination and horizontal force, from observations made at the Royal Observatory, Greenwich.

> Considering that the irregularities in the length of the sun-spot period so entirely synchronize with similar irregularities in the magnetic period, and also that the elevation or depression of the maximum points of the sun-spot curve is accompanied by similar elevations and depressions in the two magnetic curves, it would seem, in the face of such evidence, that the supposition that *such agreement is probably only accidental coincidence can scarcely be maintained, and there would appear to be no escape from the conclusion that such close correspondence, both in period and activity, indicates a more or less direct relation between the two phenomena, or otherwise the existence of some common cause producing them.*

A similar result has been reached by all investigators of this subject, both as regards the magnetic field and the frequency of auroras; also in the meteorological elements, the barometric pressure, the temperature, the wind velocity, and precipitation there is the same synchronism.

In order to show how wide the amplitude is from year to year, it was found in the sun-spot cycle 1878–1890 that the following changes took place in the northwestern part of the United States (W. B. Bulletin No. 21, p. 173):

Range in the European magnetic horizontal component,	0.000060 C. G. S.
Range in the external solar coronal field,	0.000180 C. G. S.
Range in the maximum solar (auroral) field,	0.000300 C. G. S.
Range in the northwest (the Dakotas) pressures,	0.10 inch.
Range in the northwest temperatures,	7° F.
Range in the northwest pressure amplitude,	0.06 inch.
Range in the northwest temperature amplitudes,	1° F.

These relations may need modifications whenever the scientific data warrants an improvement, but they serve to show the general connection between the various quantities involved.

It remains to be remarked that if such observational results as these are to be excluded from further consideration by Lord **Kelvin**'s theorem, then there remains little more to be done in this subject, since no other observations seem to be available. However, the same marked synchronism that exists in the 11-year period has been found to extend also most persistently in the 26.68-day period throughout the magnetic and meteorological elements. It has been shown that the periodic curve representing the mean distribution of the sun spots has an inversion in the two solar hemispheres, due to local solar action; also that the solar type curve undergoes a semiannual inversion in the year, due to the generation of opposite types of couples at the earth, in consequence of the changed presentation of its lines to the curves of the solar magnetic field at the distance of the earth's orbit. There may be a further cause for the phenomenon of inversion than the one mentioned, in the disposition of the vortices of radiation within the material of the sun. The inversion occurs at the time of a transition of the earth from one hemisphere of the sun to the other, in the course of its annual orbital motion, and it may be that the positive and negative vertices are arranged in an alternate succession on either side of the sun's equatorial plane, so that the external field has an inverted intensity in longitude, as shown by the curves of Chart 23. Such detailed and characteristic evidence of continuous touch between the solar output and the terrestrial field would seem to prove that the proper procedure is to maintain the general theorem of the direct magnetic action of the sun on the earth till its applicability is demonstrated or the above chain of facts accounted for in another way.

(2) When the variations of the terrestrial magnetic field are examined in detail, it is found that they indicate that forces have been impressed upon it which originate generally in a direction perpendicular to the plane of the orbit, and that they act athwart the normal lines of the earth's field, and therefore originate outside the earth and not inside of its surface. This excludes the view that the perturbations are caused by variations in the magnetized material of the earth, or in the hypothetical system of electric currents in the atmosphere which are assumed by some to produce the magnetism of the earth. This remark does not apply to the terrestrial electric currents which synchronize with them, but are effects in the earth's crust depending upon the preceding variations in the external magnetic field.

(*a*) The curves of Chart 26 illustrate the fact that the entire magnetic field of the earth in both the northern and the southern hemispheres, and in all longitudes, is simultaneously moved by one common impulse, and that the magnetic elements oscillate up and down synchronously in the most irregular pulsations. No meteorological system of air currents in the general or the local circulation exists which can account for the minute oscillations from which the mean curves are constructed, and therefore that source of the variation as a general terrestrial effect is excluded from the discussion, because there are, in fact, no corresponding meteorological oscillations common to the entire earth. The integral effect of numerous impulses in a magnetic field denoting solar activity may on the other hand locally modify currents of circulation having their origin in the well-known temperature gradients. The argument is not here reversible, as some might hastily assume. These curves are traces of the horizontal force as recorded simultaneously in the observatories at Greenwich, Toronto, Singapore, St. Helena, Cape Good Hope, and Hobart. Other stations might be added, but they would all agree, as is well known. It was found by an extensive, careful study of similar groups of curves, divided into periods of 26.68 days, and extending the examination from the year 1841 to the year 1896, that they can be classified into two types, each period conforming more or less closely to the typical curve, and to such an extent that the prevailing curve can usually be specified. These two types, called the direct D and the inverse I, are formed by using the same curve in inverted positions and turning it over on its longer axis, so that one curve is really employed throughout this comparison. By matching the type curve in either the direct or inverted position with each period as marked off by the 26.68-day ephemeris, as shown in the example on Chart 26, it was found that the distribution of the types, given in Table 20, is arranged in a semiannual period which is so related to critical or turning points in the earth's orbit, as concerns the position of the sun's axis, that the relation can not be accidental. The facts here assigned are entirely independent of any explanation of the cosmical cause of them, and even should the theory which I have advanced to account for them be superseded, the result will always have importance in this subject. It may be stated that for many years I have followed this semiannual inversion systematically at about fifty stations in the northwestern portions of the United States, by plotting the daily pressures and the temperatures in seven separate groups so that they form continuous lines. There is no doubt in my mind that the period and the inversion exist, and that as a means of studying the laws of the long range weather changes, it is the best that is now available for such purposes.

Synchronism of the variations of the horizontal force throughout the terrestrial magnetic field.

CHART 26.

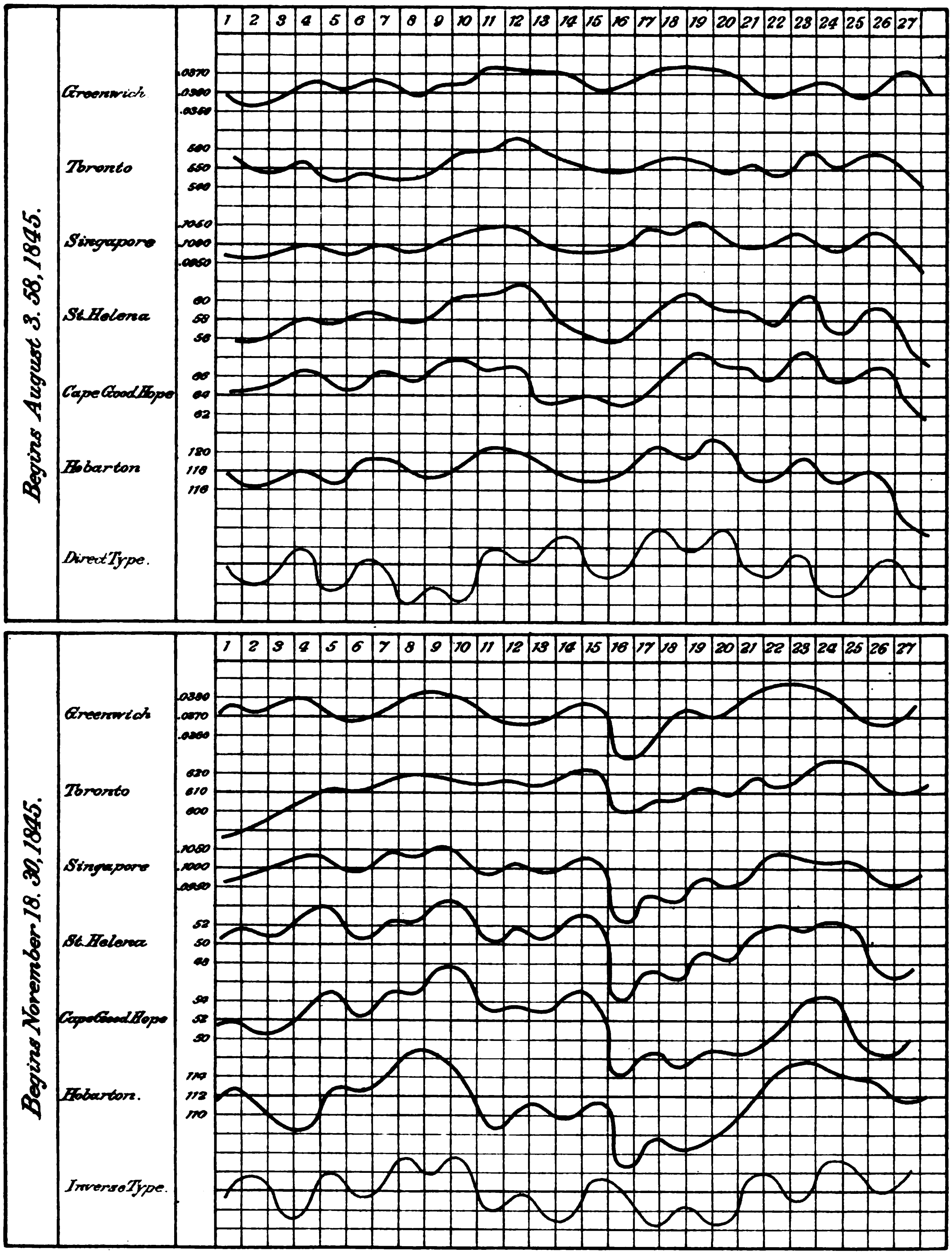


TABLE 20.—*Inversion in a semiannual period of the type recurring in the 26.68-day period.*

DIRECT AND INVERSE TYPES, FOUND BY TRIALS.

JANUARY. JULY. DECEMBER.

Periods	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1841	I	D	D	D	D	I	I	D	D	D	D	D	I	
1842	I	D	D	D	I	I	I	D	D	D	I	I	I	I
1843	I	I	D	D	I	I	I	D	D	D	D	D	I	I
1844	I	I	I	D	D	I	I	D	I	D	D	I	I	
1845	D	D	D	D	I	I	I	I	D	D	D	I	I	I
1846	I	I	D	D	D	D	I	I	D	D	D	D	I	I
1847	I	D	D	D	I	I	I	I	D	D	D	I	I	
1848	I	I	D	I	D	I	I	D	D	D				
1849	I	I	D					D	D	D	I	I	I	I
1850	I	D	D	I	I	I	I	D	D	D	D	I	I	I
1851	I	D	D	D	D	I	I	I	D	D	D	I	I	
1852	I	I	D	D	I	I	I	I	D	D	D	I	I	I
1853	D	D	D	D	I	D	I	D	D	D	D	I	I	I
1854	D	D	D	D	I	I	D	I	D	I	I	I	I	
1855	D	D	D	D	I	I	I	D	D	D	I	I	I	I
1856	I	I	D	D	I	I	D	D	D	D	D	I	I	D
1857	I	I	D	D	D	I	I	I	D	D	D	D	I	
1858	I	I	I	D	I	I	I	I	D	I	D	D	I	D
1859	I	I	I	D	D	I	I	D	D	D	I	I	I	I
1860	I	D	D	D	I	I	D	D	D	I	D	I	I	
1861	D	D	D	D	D	I	I	D	D	D	I	I	I	
1862	I	D	D	D	I	I	I	D	D	D	D	I	I	I
1863	I	I	I	D	D	D	I	I	D	D	I	I	D	I
1864	I	I	D	D	I	I	I	D	D	D	D	I	I	
1865	I	I	D	D	D	I	I	I	D	D	D	I	I	I
1866	I	I	D	D	I	I	I	I	D	D	I	I	I	I
1867	I	D	D	D	I	I	I	I	D	D	D	D	I	
1868	I	I	D	D	D	I	I	I	I	D	D	D	I	I
1869	D	D	D	D	I	I	D	D	D	D	I	I	I	D
1870	I	I	I	D	D	I	I	D	I	D	I	D	I	
1871	I	I	D	D	I	I	I	D	D	D	D	I	I	I
1872	D	D	D	D	D	I	I	D	D	I	D	I	I	I
1873	D	D	D	I	I	I	D	D	D	D	I	I	I	
1874	I	D	D	I	I	I	D	D	D	I	I	D	I	I
1875	D	D	I	D	I	I	I	D	I	D	D	I	I	I
1876	I	D	D	D	I	I	I	D	D	I	I	D	D	I
1877	I	D	D	D	I	I	I	D	D	D	I	I	D	
1878	I	I	I	D	I	I	I	I	D	D	D	I	I	I
1879	I	I	D	D	I	I	D	D	D	D	D	I	I	D
1880	D	D	I	I	D	I	I	I	I	D	I	D	I	
1881	I	D	D	D	D	D	D	I	D	I	I	I	I	I
1882	D	D	D	I	I	I	I	I	D	D	D	I	I	D
1883	D	D	D	I	I	I	D	D	D	D	I	I	I	
1884	D	D	D	D	D	I	I	I	I	I	I	I	D	I
1885	D	D	D	D	I	I	I	I	I	D	D	D	I	I
1886	D	D	I	D	I	I	I	D	D	D	D	D	I	
1887	I	I	I	I	I	D	D	I	I	I	D	D	D	I
1888	D	D	I	I	I	I	D	D	I	D	D	D	D	I
1889	I	D	D	D	I	D	D	D	D	D	I	I	I	
1890	I	D	I	I	I	I	I	I	D	D	D	I	D	I
1891	I	I	D	I	D	I	I	D	I	I	I	I	I	D
1892	I	D	D	D	I	I	I	D	D	I	I	I	I	I
1893	D	D	D	I	I	D	D	D	I	I	I	D	D	
1894	I	I	D	D	D	I	I	D	D	I	I	I	D	D
D	17	32	42	41	18	7	13	33	43	41	30	16	10	12
25	—8	+7	+17	+16	−7	−18	−12	+8	+18	+16	+5	−9	−15	−13

GENERAL LAW.

	I	D D D Max.	I I I Min.	D D D D Max.	I I I Min.

Tables 21 and 22 contain two examples, taken quite at random from my numerous computations, of the fact that generally the horizontal and vertical components move in opposite directions, and we know that the impulse is quite closely confined to the magnetic meridians. Table 21 gives these components for the disturbance of February 12, 1892, the coordinates having been computed for several selected epochs, chosen for measurement of the deflection of the traces on the photographic registers. While there are many exceptions, the two components have usually opposite signs. The horizontal component is much more reliable than the vertical for two reasons: (1) It is the stronger component in middle latitudes where the stations are located, and (2) the Lloyd balance-magnet does not always behave sensitively and register the external impulse accurately, as can be inferred from the discrepancies existing at neighboring stations which can not be entirely due to the actual stresses in the magnetic field. Table 22 gives an example of the coordinates, not selected for individual minutes, but as the mean values of the twenty-four hourly observations contained in the published reports. It should be noted that the vertical force is less satisfactory than the horizontal for the reasons just given, and that the complete record in both components was not available for all the stations. The horizontal component *dx* shows that there is a synchronous impulse involving the entire earth. The vertical component *dz* is usually of opposite sign to *dx*, if the impulse is pronounced and strong. By taking the sum of the means of *dx* . *dz* in the last column for those days when *dx* . *dz* have opposite signs, we have 1067+358=1425; for the days having like signs, 434+155=589; so that the ratio is about 3 to 1 in favor of the unlike signs. This month was taken as a specimen of the prevailing facts, and is not in itself a very favorable example. There are some days when the magnetic deflecting force is feeble and indecisive, so that the normal field may be conceived as swaying about in an aimless manner. It is on this account that the vertical force is so troublesome, and besides this the observations generally have a tendency to be discordant at neighboring stations.

Since the component *dy* averages very small when the daily means are computed, the *dx* . *dz* impulse is necessarily directed along the meridians; since *dx* . *dz* have in general opposite signs, they can not arise from the same cause that produces the earth's normal field; the direction is easily found by plotting the vectors on the plane of a magnetic meridian, and it is across the normal field, so that the combined vector system developed for the entire earth is evidently part of a magnetic field perpendicular to the plane of the orbit, and, by inference, we refer its source to the sun as a magnetic body. The components of the system producing the variations of the field from day to day, and also the disturbances, are entirely different in structure from those producing the hourly variations within the diurnal period, and they can not be derived from the same source. The latter are attributed to the effect of the electromagnetic radiation of the sun within the earth's atmosphere, as will be presently explained. This set of facts, both in general and particular, seems to me to be entirely inconsistent with the view that the solar magnetic field does not continuously modify the terrestrial field, and with the theory that a system of electric currents is generated by the solar radiation whose electro-magnetic effects produce the observed perturbations.

The two problems of the immediate future in terrestrial magnetism are as follows: (1) Is the magnetization of the earth, the other planetary bodies, and the sun due to their rotation in the ether, or to an internal process akin to ionization, or to molecular motions? All studies on the effect of rotation in the ether have heretofore shown that the resultant magnetic force is very feeble, if it exists at all. There is a probability that the atomic actions in the interior of these large bodies produce electric and magnetic forces which develop a planetary magnetism in conjunction with the prevailing high temperature. I am inclined to view the last proposition more favorably than the other. (2) Is the disturbance phenomenon of the earth's normal field due to effects transmitted in the electro-magnetic radiation or in a direct polar magnetic field? Some students are expecting to find in the action of the different kinds of waves transmitted in the sun's radiation an explanation of the diurnal and of the disturbance magnetic deflecting fields. These are, however, entirely different in their characteristics, and I believe that the view that they are both to be referred to one radiation must break down upon this fact.

TABLE 21.—*Rectangular components during the magnetic disturbance, February 12, 1892.*

	Horizontal deflecting force=0.000001 *dx*								Vertical deflecting force=0.000001 *dz*							
Time of impulse	San Antonio	Washington	Greenwich	Paris	Potsdam	Vienna	Pawlowsk	Melbourne	San Antonio	Washington	Greenwich	Paris	Potsdam	Vienna	Pawlowsk	Melbourne
12.00	−144	−144	−108	− 94	− 78	....	+ 42	+ 20	−40	....	+ 13	+ 47	+ 22	....	+ 106	−30
1.00	−144	−252	+ 20	− 59	+ 57	....	+387	+ 40	−50	....	+ 55	+ 84	+ 63	....	+ 324	−22
1.45	−211	−276	− 9	− 53	+ 26	− 18	+387	− 80	−60	....	+156	+153	+100	+56	+ 401	−26
2.08	−202	−324	− 44	− 73	− 52	−107	+387	−100	−60	....	+195	+169	....	+74	+ 372	−19
3.00	−225	−264	− 12	− 68	....	−135	+387	−100	−50	....	+221	+223	....	+93	+ 442	−19
3.20	−238	−252	+ 99	− 4	+ 10	−115	+387	+ 60	−50	....	+234	+251	....	+99	+ 442	+30
3.40	....	−300	+180	+ 97	+135	−111	+371	−160	....	....	+234	+260	....	+99	+ 413	+15
4.25	−270	−360	+ 93	− 50	− 31	−131	+238	−140	−40	....	+221	+325	....	+93	+ 372	+15
4.35	−283	−360	+ 75	+ 23	+ 42	− 74	+371	−160	−40	....	+221	+325	....	+93	+ 283	+19
5.20	−265	−360	+261	+125	+172	− 25	− 53	−140	−35	....	+221	+325	....	+93	+ 147	+22
6.00	−288	−360	+ 35	− 62	− 42	−107	0	−100	− 5	....	+234	+325	....	+87	+ 136	+37
6.25	−283	−180	....	+ 17	− 94	− 94	−148	−100	0	....	+234	+325	....	+81	+ 100	+41
6.53	−297	−192	....	+ 30	− 16	−135	− 42	−100	−20	....	+234	+223	....	+68	− 118	+52
7.10	−247	− 36	− 18	− 68	− 47	−139	−223	−110	+40	....	+234	+205	....	+56	− 242	+56
7.19	−301	− 48	....	− 15	− 47	−148	−334	−160	+10	....	+208	+214	....	+56	− 165	+67
7.38	−292	−108	....	− 39	....	−189	− 26	−120	+15	....	+195	+187	....	+62	− 118	+75
8.30	−301	− 48	−116	−144	−208	−266	−450	−260	+25	....	+182	+177	+100	+56	− 94	+82
9.25	−270	+216	−102	−129	−156	−217	−768	−310	+45	....	+156	+139	+ 70	+43	− 227	+97
9.55	−256	+ 24	−270	−289	−354	−328	−821	−330	+60	....	−122	+ 84	+ 50	+50	− 336	+97
10.26	−270	+ 96	....	−205	−218	−266	−297	−290	+55	....	+ 26	+121	+ 8	+31	− 283	+90
10.52	−256	− 72	−139	−121	−135	−185	−291	−280	+50	....	+ 57	+112	+ 45	+43	− 260	+75
11.26	−243	− 72	....	−114	−177	−201	−360	−290	+40	....	+ 55	+ 93	+ 20	+19	− 442	+52
11.45	−256	− 78	+ 69	−144	− 36	− 82	−970	−310	+20	....	− 26	− 19	− 80	+19	− 667	+22
12.26	−283	− 24	....	+152	−281	+ 41	−968	−200	+50	....	−156	−149	....	− 6	−1091	−30

+*dx* = increasing horizontal force northward in both hemispheres.
+*dz* = increasing vertical force downward in the northern hemisphere.
−*dz* = increasing vertical force upward in the southern hemisphere.

If *dx* and *dz* have opposite signs, the deflecting force lies athwart the normal magnetic field. The disturbances generally begin as vectors directed southward near the meridian, downward in the northern, and upward in the southern hemisphere. (W. B. Bul. No. 21, p. 78.)

TABLE 22.—*The horizontal and vertical deflecting forces, dx. dz, which generally have opposite signs. Example for March, 1887.*

March 1887	Horizontal deflecting force=0.000001 dx											Vertical deflecting force=0.000001 dz							Means	
	Los Angeles	Toronto	Green-wich	Paris	Pola	Prague	Vienna	Paw-lowsk	Tiflis	Zi-ka-wki	Batavia	Green-wich	Paris	Prague	Vienna	Paw-lowsk	Tiflis	Batavia	*dx*	*dz*
1	+32	+26	−23	+50	+22	+119	+31	+44	+3	−11	+20	+72	+70	−3	−69	+22	+68	−75	+28	+12
2	+68	+68	−1	+67	+59	+138	+38	+13	+22	−52	+38	+82	+45	−3	−79	+20	+27	−81	+42	+2
3	+102	+76	+41	+84	+96	+188	+90	+62	+110	+7	+79	−10	−30	−25	−95	−12	+26	−97	+85	−35
4	+102	+101	+37	+80	+83	+237	+85	+51	+118	+97	+126	+18	−5	−3	−92	−5	+25	−93	+102	−22
5	+7	+75	+2	+47	+60	....	−2	+10	+46	+66	+170	+63	+40	....	−101	+33	+24	−39	+44	+3
6	−74	−50	−110	−56	−63	....	−103	−81	−86	−135	−24	+78	+44	....	−12	+20	+52	+75	−78	+43
7	−16	−8	−91	−10	−36	....	−108	−32	−108	−145	−48	+96	+58	....	−21	+68	+60	+53	−60	+53
8	−90	−96	−88	−23	−9	....	−109	−73	−49	−86	+19	+62	+22	....	−38	+76	+9	−4	−60	+21
9	−42	−71	−143	−96	−82	....	−164	−144	−140	−217	−111	+98	+46	....	+2	−26	+98	−53	−121	+27
10	−45	−42	−20	+41	+5	....	−57	−45	−12	−147	−7	+7	+10	....	+11	+12	+37	−12	−33	+11
11	−32	−37	−55	−13	−28	−136	−87	−36	−23	−108	+33	+40	+14	−33	−4	+29	+16	−8	−47	+8
12	−26	+2	−55	−17	−31	−77	−63	−17	−25	−118	+15	+54	+8	−46	+22	+34	−15	−11	−37	+7
13	+23	−18	−72	+28	+36	−108	−15	+12	+24	−9	+20	+68	−78	−16	+37	+4	+43	−44	−8	+2
14	+71	+26	−62	+56	+127	−89	+13	+1	+42	−69	−29	+12	−54	+48	+5	+2	+19	−55	+8	−3
15	−15	−31	−49	−80	+40	−50	+37	+20	+50	−90	−18	−70	−50	+85	+18	+20	−10	−55	−17	−9
16	−29	−44	−144	−81	−88	−111	−94	−61	−31	−62	−68	−50	−92	−35	+35	−39	−5	+43	−74	−20
17	+44	−31	−49	+29	+4	−92	+23	−1	+8	−84	−88	−47	−104	+46	+8	+11	0	+79	−21	1
18	+84	+51	−46	+28	+37	−32	+56	+19	+47	+134	+1	−105	−66	+62	−1	+11	−5	−19	+34	18
19	+124	+76	−3	+78	+70	−3	+112	+88	+57	+172	+32	−98	−27	+27	+2	+21	−10	−37	+73	−17
20	+20	−10	−46	+47	+52	−13	+83	+38	+76	+250	+92	−124	−18	−29	−37	+2	−15	−92	+54	−45
21	−31	−51	−149	−64	−56	−124	−39	−22	−75	+48	−44	−90	+41	+67	−42	+12	−50	+23	−55	−5
22	−30	−47	−43	−44	−54	−75	−1	−23	−56	+126	−10	−188	+60	+21	+46	−8	−115	−35	−23	−31
23	−144	−109	+60	−5	−32	−5	−4	−13	+3	+94	+34	−194	+78	−25	+25	−27	−110	−33	−11	−41
24	−80	−69	+28	−86	−70	−46	−52	−53	−68	−28	−94	−177	+16	+61	+54	−67	−5	+30	−56	−12
25	+26	+9	+103	−26	−8	+64	+11	+36	−39	+90	−14	−117	+55	−8	+58	+13	−80	−16	+23	−13
26	−3	−5	+103	+3	+24	+53	+29	+16	+40	+98	+48	−93	+73	+38	+56	+24	−125	+53	+37	+3
27	+37	+34	+117	+2	−4	+42	+50	+6	+9	−45	+11	−41	+71	+3	+67	+24	−119	+69	+24	+11
28	−8	+19	+102	−18	−12	+2	+43	−5	−2	−77	−24	−3	+60	−9	+70	+24	−203	+86	+2	+5
29	+65	+31	+139	+61	+110	+1	+93	+5	+17	−30	+35	−30	+18	+14	+5	+4	−117	+81	+48	−4
30	+128	+37	+162	+80	+133	+40	+103	+65	+86	+58	+57	−28	−4	+31	−22	−35	−141	+69	+86	−19
31	+135	+82	+150	+130	....	+90	+100	+105	+125	+85	+100	+15	−5	+65	−49	−25	−135	+66	+110	−10

Sums of last columns taking the unlike signs is 1425; taking the like signs is 589.

In the time of disturbances the ordinary diurnal vectors are superseded and transposed into a different field at right angles to the ecliptic. If they did come from the same source, this could never happen, because the disturbance field would be an intensified diurnal field, which is not the case. Furthermore, the variability of the diurnal magnetic field ought to have a corresponding change in the intensity of the solar radiation, which has not been observed, for the atmospheric absorption can hardly mask the heat fluctuations if they have so pronounced counterpart variations in the magnetic field.

PHYSICAL PROCESSES IN THE EARTH'S ATMOSPHERE.

After having deduced certain results from an extensive computation on the magnetic deflecting forces in the earth's field, a brief account of which may be found in Bulletin No. 21, great difficulty was encountered in matching them with any known physical processes likely to take place in the atmosphere. In consequence of this defect the discussion halted till such advances had been made in experimental physics as would warrant taking up the incomplete exposition. At that time, 1897, but little progress had been made in explaining several facts which have since been accounted for by the theory of ionization, so that no advantage could then have been taken of a theory which had not passed beyond the stage of experimental hypothesis. But the case is now different, since the nature and action of the ions in a gas are well understood, and since it has been shown by Elster and Geitel that the theory of ionization is best fitted to cope with the perplexing contradictions which have been observed in the phenomenon of atmospheric electricity. This, in addition to the fact that ionization in the sun seems to constitute a very complete theory of the phenomenon of the solar corona in connection with a magnetic field, encourages us to expect that ionization in the earth's atmosphere, in conjunction with the solar and the terrestrial magnetic fields, constitutes the missing links which have so long baffled our research.

We may at this point confine our attention to two phenomena explained in Bulletin No. 21: (1) That the diurnal deflecting vectors seem to be generated as if the electro-magnetic or sunlight field had also the properties of a magnetic field; and (2) that the curve of intensity of the polar field at the earth is a wave line (p. 64) which differs considerably in form from that produced by plunging a permeable sphere or shell into an external magnetic field. Regarding the first phenomenon, it was stated that the required magnetic properties of the sunlight radiation was associated with atomic conditions (pp. 17, 34, 44, 79, 80, 81, 91, 164). On page 174 one reads:

> It is admitted that during the mutual readjustments of the magnetic field, currents of electricity exist throughout the atmosphere; also a change in the wave lengths of the electro-magnetic external field may be a source of the atmospheric electricity; but these subjects must be more fully studied, if possible, before a decisive statement can be offered. The synchronism between the solar and the terrestrial phenomenon, the periodicity and the inversion of types in the polar field, the peculiar distribution of the magnetic vectors in the electro-magnetic field, are therefore the chief points to be explained on the atmospheric electro-current theory. These currents, as well as the earth-electric current, are necessary consequences of the interaction of the three fields described, including their own variations in strength and the induced variations due to motion of the planet. But it is hardly possible to consider such electric currents as the true source of all the phenomena heretofore mentioned in detail.

Regarding the curve of intensity, a complete theory of the direction of the lines of force was given, namely, that the earth as a permeable shell is immersed in an external magnetic field generated by the sun, in which it was shown that the *direction* of the deflecting vectors at 26 stations agrees remarkably well with that of the theoretical lines of force deflected under such conditions. Regarding the intensity of the force nothing was said, because my ideas on the subject were at that time not sufficiently clear. Of course these incomplete statements laid my work open to adverse criticism by those who chose to be unfavorably impressed, but at the same time I believe it will be recognized that a very close approach was made to the heart of the problems involved, and that in fact there is but little to recall, because advance in recent physics points in exactly the same direction as that in which my own research was moving. It seemed to me especially important to discard two theories which are in vogue regarding the causes of terrestrial magnetic variations, namely: (1) The meteorological system of convectional air currents, because the facts of synchronism could not thus be established, and because the well-known mechanical convection has not the speed and direction necessary to produce the observed secondary magnetic field. (2) The atmospheric electric currents adopted by many magneticians were excluded, because the ether and the atmosphere are practically nonconductors, and prohibit widely extended currents of electricity from circulating around the earth. The conductivity which is due to various physical processes, such as ionization, is entirely too small to permit the induction of general magnetic fields by means of electric currents. The atmospheric conductivity is not large unless the air is highly rarefied, far below that of the atmosphere except on the outermost stratum, where the pressure is about 1 millimeter; and it is confined to the immediate neighborhood of the place of special processes, such as are produced by flames, electric discharges, cathode, Röntgen, Becquerel, ultra violet and other radiations. Nearly all the authors who have worked along these lines, as Schuster, Schmidt, and others, ascribe more conductivity to the atmosphere than seems to be justified by the facts. If the conductivity becomes metallic under restricted circumstances, then this must not be ascribed to the air generally, in order to produce the required magnetic fields, unless it can be proven that such special conditions exist. The conductivity accompanying ionization, which is simply due to the slow diffusion of minute charged particles, is of another order; the magnetic field attending it is of atomic origin *in situ*, and it is integrated by an application of the Ampèrean principle into a magnetic field, like an ordinary polar field with a potential.

PHYSICAL EXPERIMENTS ON RAREFIED GASES.

The facts derived from recent experiments are very numerous and important, but it is quite impracticable to attempt to reproduce many of them here. Numerous researches are conducted by means of vacuum tubes on account of the ease of their practicable manipulation; they are constructed with electrodes sealed in the ends for direct electric discharges, or they are electrodeless, provided with a coil outside, through which an oscillating electric current is passed. In these tubes one can study the relations of,

$p =$ the pressure of the gas in the tube in millimeters.
$d =$ the thickness of the Hittorf dark space in millimeters.
$i =$ the current in amperes.
$V =$ the tension in volts.
$E =$ the work done in watts.

The following example of these relations is taken from, "Unsichtbare Vorgänge bei elektrischen Gasentladungen," von H. Ebert, K. bayer. Akad. d. Wiss., 1898, Bd. XXVIII, Heft IV, page 503.

Table 23.—*Relations of the pressure, thickness of the Hittorf dark space, current, voltage, and work done in the vacuum tube under conditions of the greatest conductivity of air.*

p	2.76	1.30	0.83	0.51	0.27	0.20	m. m.
d	0.9	1.5	2.2	2.8	5.0	6.7	m. m.
i	12.61	15.76	15.94	15.39	13.49	12.37	m. amp.
V	718	574	559	602	725	812	volts.
$iV \times 10^3 = E$	9.05	9.06	8.98	9.27	9.77	10.06	watts.
Successive phenomena observed	Unstratified light		Light meets in the middle.	Stratification and striæ prevail			

It is seen that as the pressure continues to decrease the thickness of the Hittorf dark space increases, the current reaches a maximum and then diminishes; the voltage and the rate of doing work alike arrive at a minimum and then increase. The reversal of the electrical pressure indicates that a point is reached where the glowing unstratified light, extending out from the ends of the tube as rarefaction increases, meets in the middle and then, upon further decrease of pressure, breaks up into the striæ which are characteristic of the vacuum tubes. A mathematical analysis of this phenomenon is given by J. J. THOMSON (Phil. Mag., March, 1899, XIX); this is extended by J. H. JEANS (Phil. Mag., March, 1900, XX) on the striated electrical discharge (compare Table 38). H. EBERT'S experiments include tubes of different forms and dimensions, and with variable distances between the electrodes. There is found to be a relation between the "reversal pressure" and the wave length; the resistance and conductivity extend throughout the gas, but they differ in different parts of it; the action leading to increased conductivity occurs first along certain paths, and then passes over into others as the conditions vary; the action of a magnetic field is to quench the light; electro-motive forces of resistance are developed. The order of the process is somewhat as follows:

(1) Discharges of electricity.
(2) Ionization of the gas in rarefied spaces.
(3) Increase in conductivity.
(4) Increase in electrostatic potential.
(5) Reversal pressure effect.
(6) Shifting the path of transmission effect.
(7) Diffusion of the ions with different velocities.
(8) Effect of the magnetic field to quench, deflect, or change the light.

The phenomena of the deflection of a cathode stream by a magnetic field in its neighborhood, the helical rolling of the paths of the cathode rays by a superposed magnetic field, which show that the magnetic lines of force are vortices in the ether about their axes, and that the motion of the ether is rotational within them, are so well known that we may pass to a fuller statement regarding the action of the electrostatic force upon small masses charged with electricity, such as compose the cathode rays, or the ions into which air and aqueous vapor may be decomposed under certain conditions. A paper by H. EBERT, "Das Verhalten der Kathodenstrahlen in Electrischen Wechselfeldern," Ann. der Physik und Chemie, 1898, Band 64, contains the description of experiments applicable to this subject. A BRAUN'SCHE vacuum tube, provided with a diaphragm and screen for observing the position of the bundle of cathode rays, is placed between two small plates which form the ends of an open circuit. The wires lead to a transformer such that a current, with maximum voltage 2149 and period number 520, discharges across the tube at the point of the diaphragm. The electrostatic force is observed to vary in a smooth sine curve, and it is found that the ends of the cathode rays also execute precisely the same curve; this is shown by means of a rotating mirror formed of phosphorescent material which serves to retain and draw out the image. The evidence is positive that the position of the charged particles in the cathode rays pulsates synchronously with the vibrations of the electrostatic field. The question is discussed whether it is the magnetic force which is generated by the varying electrostatic field according to the law of curling,

$$\text{curl } \mathbf{H} = \omega c \frac{d\mathbf{E}}{dt}, \quad \text{where}$$

ω = the area of the electrostatic field (the plates).

c = the dielectric constant of air $= \frac{1}{9 \times 10^{20}}$.

$\mathbf{E}$ = the electrostatic force.

$\mathbf{H}$ = the line integral of the magnetic force in a circuit around the edge of the plates.

The deflection produced by bringing a small magnet near the cathode bundle was 3 centimeters for a force of 0.1200 C. G. S. The same deflection is produced under circumstances such that the value of $\mathbf{H}$, computed by the formula, curl $\mathbf{H} = \omega \,.\, c \frac{d\mathbf{E}}{dt}$, is only $\frac{1}{300000}$ part of that quantity.

Hence, the conclusion follows that it is not the induced magnetic forces in a pulsating electrostatic field which produces the observed deflection. This is, however, accounted for as follows: When cathode rays are generated in rarefied gases in a tube by electric discharges across the space of low pressure, the sides of the containing tube are heavily charged with static electricity, negative near the cathode and positive near the anode, on the inside of it. The uniform distribution of these charges on the walls of the tube hold the cathode rays in the center by an equally distributed electric pressure on all sides. Now, if this distribution is disturbed by the approach of an electric or a magnetic body to one side of the tube, the cathode rays bend to conform with the new position of equilibrium. The action of the small condenser plates on the outside of the tube was to periodically disturb the electric pressure as represented by a sine curve, so that the end of the cathode bundle moved synchronously with it. This shows that changes in an electrostatic field are followed by corresponding variations of position of the charged particles of the cathode bundle. **Ebert** also balanced a magnetic force against an electrostatic force, the two fields being at right angles to one another, and the result was that when the fields were pulsating synchronously the end of the cathode bundle executed well-defined **Lissajous** figures, which means that the charged particles are equally subject to deflexion by magnetic and electrostatic forces.

Now the charged particles or ions in the atmosphere likewise respond to the variations in the electrostatic and the magnetic fields which traverse it, and these two fields must react upon each other through the medium of the ions. If the ultra violet radiation, from the sun or any other source, generates ions at one point in the atmosphere more abundantly than at others, and if at some points the ions recombine and eliminate their electrostatic effects by forming neutral masses, then it follows that both the electrostatic fields and the magnetic fields must be deflected, and take up new positions in harmony with these changes. *This is evidently a sufficient cause for the diurnal variations of the magnetic field, and of the atmospheric electric potential fall or gradient.* There is thus no need to invoke electric conduction currents to account for the phenomena of the diurnal magnetic deflections. Indeed the nonconductivity of the air is not sufficiently overcome by ionization to permit such currents to induce enough magnetic force, especially so as under the very favorable conditions of the **Ebert** transformer, with 520 pulsations per second, the magnetic force is much too small. If in the air we require a deflecting force of about 0.00012, then with a pulsation of 150,000 per second there would be something like the right order at the same voltage. At higher voltage, as 15,000 per centimeter, the periodicy could be decreased. This order of electric and magnetic quantities can not be wholly improbable in the air, so that there may really be some magnetic effect due to rapid minute variations in the atmospheric electricity. **Ebert** also observed true phosphorescent light at the glass just beneath the electrostatic plates when undergoing vibrations. These experiments make it quite clear what kind of processes in the atmosphere give rise to the phenomena of the terrestrial magnetic and electric fields without resorting to other less probable theories. In order to bring the facts of atmospheric electricity together for comment, a brief recapitulation of certain results will be given.

THE PHENOMENA OF ATMOSPHERIC ELECTRICITY.

Elster and **Geitel** have recently applied the theory of ionization in the atmosphere to account for the phenomena of atmospheric electricity with considerable success, so much so in fact that it is by far the most promising theory on the subject. M. A. B. **Chauveau** estimates that there are about thirty well-defined theories of the origin of atmospheric electricity, some vague and improbable, others accounting at least in part for certain features in the complex conditions. That electricity should be generated in many ways at the earth's surface and in the air itself is probable, but the important object for science is to acquire a working hypothesis of the cause and action of the great part of it. The older theories of **Exner**, that electrification is chiefly associated with the evaporation, condensation, and convection of aqueous vapor, and of **Elster** and **Geitel**, that the escape of negative electricity is accelerated by the action of ultra violet light on metallic and other surfaces, have been perhaps most considered of late years.

The latter has, however, been modified in favor of the ionization theory, which we shall briefly recapitulate.

The electrostatic lines of force in the atmosphere are practically vertical, and the higher strata are positively charged, while the surface of the earth is negatively charged in normal conditions. The electric gradient is approximately 130 volts per meter, but it decreases upward and, according to balloon observations, *disappears at an altitude of about 5,000 meters*, where the lower cloud system may be assumed to terminate. If the surface of the earth is level the vertical lines are nearly parallel; if it is mountainous the lines of electrostatic force concentrate on the peaks and forsake the valleys, so that the equipotential lines become curved and are perpendicular to the gradient lines, the peaks being more highly charged than the valleys. If a positive charge of electricity moves downward and a negative charge moves upward, there is an electric current from the air to the earth which is called *negative;* if a positive charge moves upward and a negative downward a *positive* current passes from the *earth to the air.* Displacement currents are caused by local temporary disturbances and readjustments of electricity.

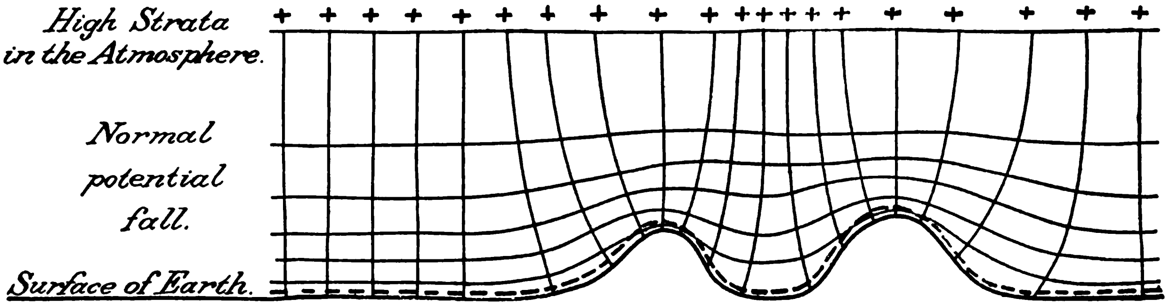


CHART 27.—Scheme of the distribution of the electrostatic lines of force in the atmosphere.

If c=the permittivity or dielectric constant$=\frac{1}{9\times10^{20}}$,

$\mathbf{E}$=the electrostatic force,

$\mathbf{D}$=the displacement, we have, $\frac{c\mathbf{E}}{4\pi}=\mathbf{D}$.

Then $\omega\,.\,c\frac{d\mathbf{E}}{dt}=\omega c\dot{\mathbf{D}}=\text{curl }\mathbf{H}$=the line integral of the magnetic induction $\mathbf{B}$ which is equal to the magnetic force $\mathbf{H}$ in the atmosphere around the bounding curve of the surface ω.

The electric lines of force are associated in tubes; an electric displacement along the axis of each tube generates a magnetic force around the tube such that, $4\pi\times$ current through the closed curve=the line integral of the magnetic force round the curve=curl $\mathbf{H}$.

$$\omega c\dot{\mathbf{D}}=\omega\,.\,c\,.\,\frac{d\mathbf{E}}{dt}=\text{curl}_\omega\,\mu\mathbf{H}=\text{curl}_\omega\,\mathbf{B}.$$

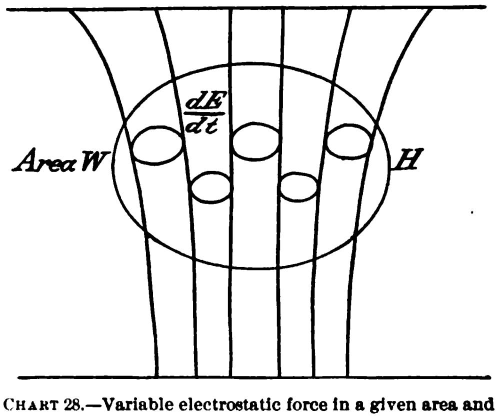


CHART 28.—Variable electrostatic force in a given area and the resulting magnetic force.

In the electrostatic system of units the magnetic inductivity for air is $\mu=1$, and since $\mu cv^2=1$, where $v=3\times10^{10}$, the velocity of light or the ratio of the electrostatic units to the electromagnetic units $c=\frac{1}{(3\times10^{10})^2}$. The line integral around a bundle of single tubes is by the Ampèrean principle and by STOKES theorem equal to the line integral around the bounding surface. As already stated, the magnetic force is usually very minute in the displacement of electricity in the atmosphere, though it may be considerable in the case of a lightning discharge. The electrification at any point is ρ=divergence $\mathbf{D}$, that is the degree of concentration of the electrostatic lines within an area as referred to the normal number belonging to the area.

This is illustrated over mountain tops where there is convergence, and in the valleys where there is divergence. If the medium containing electrification is moving through the ether with the velocity $\mathbf{u}$ there is a motional current $\rho\mathbf{u}+\mathbf{j}$. This is the case in the atmosphere, since there is a steady drift eastward in the higher latitudes and a westward drift in the lower or tropical latitudes. The amount of magnetic force developed by this mechanical circulation is not large, but it has been utilized by TRABERT (Met. Zeits., Nov., 1896, p. 410) to account for certain phenomena in atmospheric electricity which, however, are more probably due to ionization. There is still another source of current in the atmosphere depending upon the conductivity of the air, k, where $\mathbf{C}=k\mathbf{E}$. This quantity k is the one which is vanishingly small in pure nonconductors, as the ether and normal dry air, but which has been practically assumed by some authors to be large enough to permit the atmosphere to be traversed by long and persistent electric currents capable of inducing true magnetic fields. Thus the permanent magnetism of the earth has been referred to that source; certain local deflections of the normal magnetic field have been assumed to depend upon local electric circuits equivalent to a ring circulation (Ad. Schmidt, Meteorol. Zeit., Sept., 1899, p. 385, and Terr. Mag., March, 1890, p. 9) with the well-known distribution of magnetic induction $\mathbf{B}$. These electric currents are said to be located in the lower strata of the atmosphere, and they may not be referred as such to the thin high stratum where the conductivity is greatly increased in consequence of the extreme rarefication of the gaseous medium. We shall enlarge upon the conductivity factor in the next section. It is finally to be concluded that the total electric current is

$$\mathbf{J}_o=\mathbf{C}+\dot{\mathbf{D}}+\rho\mathbf{u}+\mathbf{j}=k\mathbf{E}+\frac{c}{4\pi}\frac{d\mathbf{E}}{dt}+\rho\mathbf{u}+\text{curl}\,V.\,\mathbf{Dq}=\frac{\text{curl}\,(\mathbf{H}-\mathbf{h}_o)}{4\pi},\text{ per unit area.}$$

THE DIFFERENT SOURCES OF MAGNETIC FORCE IN THE EARTH'S ATMOSPHERE.

The first term $k\mathbf{E}$ is the current depending on conductivity, and if the atmosphere possessed something like metallic conductivity, it would be the seat of continuous electric currents through the air, which would induce true magnetism, just as the electric earth currents do in the body of the solid earth. It can be shown clearly that within the region open to the exploration of atmospheric electricity there exists no conductivity comparable with that in the earth, and such experimental measures have already been carried to great heights in balloon ascensions, 16,000 meters. The second term gives the displacement currents per square centimeter, and these are the oscillations which occur along the electrostatic lines, as from the cloud to the earth in lightning discharges. It is probable that there exists a pulsation at such times more or less pronounced along the electric lines in a vertical direction, and a magnetic force due to such vibrations would be developed whether they are periodic or not. The fact that photographs of lightning discharges show that the air is cracked or fissured like brittle glass, and that the electricity apparently forces its way only after a breakdown of the dielectric takes place, indicates that normally the air is a powerful nonconductor, but that during the lightning discharge ionization takes place rapidly, and the zigzag paths of light probably show where the air is most susceptible to dissociation and to an increase of conductivity. The third term indicates that an electric current may be formed by the rapid transference of the electric density from one point to another. Thus the passage of electric currents in the earth may disturb the surface density, or the physical processes in cloud formation may cause a change in the place where the positive charges congregate together. Such changes in electric density in the upper and lower strata cause a shift to take place laterally in the electrostatic lines. These are no doubt perpetually swaying to and fro in the atmosphere. In consequence of the motions of the electrostatic lines from side to side there is generated the current $\rho\mathbf{u}$ at a given place, and this, too, is the source of a magnetic field, Finally, the fourth term $\mathbf{j}=\text{curl}\,V.\,\mathbf{Dq}$ means that if the medium itself is in motion so that the electric displacement $\mathbf{D}$ is moving with the velocity $\mathbf{q}$ there is formed a magnetic force at right angles to the plane $\mathbf{Dq}$. Thus in the atmosphere we have electrostatic lines stretching vertically up and down, and they are moving eastward with a velocity $\mathbf{q}$ in the higher latitudes, or westward in the lower latitudes, so that there is generated magnetic force pointing *northward in the higher latitudes, but southward in the lower latitudes.* The vector product rule is that *V*. **Dq** signifies that if **D** is positive upward and **q** is motion eastward, then by right-hand rotation of **D** to **q** the magnetic force is northward; or if **D** is positive upward and the motion westward, as in the Tropics, then there is magnetic force southward. The rotation curl *V*. **Dq** means that the generation of the magnetic force *V*. **Dq** is accompanied by the electric current around it as an axis, in accordance with the line integral or curl principle. Furthermore, it should be noted that since the strata of the atmosphere move faster above than below in the higher latitudes, there must be a distinct variation in the displacement **D**, which is another way of giving rise to the second term type of currents, and it should be added to those already described as oscillations along the electrostatic lines of force. Likewise, the motions of the atmosphere in cyclonic and anticyclonic circulations give rise to other variations in the displacement, so that a very complex system of conditions really binds together the electric and the magnetic fields in the atmosphere. Since action is equal to reaction, it follows that when the polar magnetic field from the sun impinges on the earth's atmosphere, any oscillations in it caused by solar pulsations must be resolved through a similar train of physical processes, first to the ions of the atmosphere, and thence to the gaseous masses which enter into the ordinary meteorological circulation. Thus a true physical connection is established between solar and terrestrial magnetic forces, and between these and the circulation of the atmosphere in storm circulation. From this point onward one can do little more than repeat the statements which have already been published in Bulletin 21 of the Weather Bureau. We will therefore emphasize some of the points which more closely concern the process of ionization in the atmosphere.

Referring now to Chart 27, which shows the courses of the normal electrostatic lines between the air and the earth, the theory of ionization supposes that in undisturbed normal air an equal number of positive and negative ions exist, but that in the case of a conductor surrounded by ionized air the negative ions always seek the conductor; hence, in the case of the earth it must be negatively charged with electricity while the atmosphere is positively charged. The weak point in the theory is to show how and why the atmosphere becomes thus heavily ionized, how the molecules or atoms of air and aqueous vapor become dissociated on a large scale, even admitting that conditions exist for producing ions to a limited extent. One naturally assumes that it is the ultra violet radiation of the sun which causes the dissociation, but ELSTER and GEITEL remark (Terr. Mag., Dec., 1899, p. 230):

> Where the source of this condition is to be sought remains as yet unanswered, though it is probable, since the conductivity increases with the height, that it lies in the higher strata of the atmosphere. As yet there exists no ground for referring it back to an action of the sunlight.

However, since the ions really exist in the atmosphere, their history may be followed with some degree of accuracy. If by dissociation the ions are produced in the upper strata, then by gravitation acting upon them and by diffusion they seek the surface of the earth, which is a conductor. The property of the negative ions to travel faster than the positive ions is due to the much smaller masses of the carriers of the negative charges. The negative ions arrive at the surface in greater numbers than the positive, and thus by accumulating a charge which repels other negative ions there is built up a balance between the gravity, which draws the ions down, and the electricity, which repels them upward, so that an electrostatic equilibrium tends to become established. Therefore the work which is represented by the tension along the lines of force in an electrostatic field is to be referred to the action of gravitation. The charges travel by the way of the lines of force, and seek the mountain peaks, the valleys, or the plains, as the case may be. These are the conditons which belong to clear weather.

In obscure weather, when mist, fog, smoke, and condensation products prevail in the atmosphere, as in certain zones of the earth more than in others, as in cyclonic areas relative to anticyclonic, in the afternoon relative to the forenoon, the foregoing state of affairs is somewhat modified. The negative ions have been shown to serve, just like dust particles, as the nuclei of condensation for aqueous vapor, so that rain drops are readily built up around them. But an ion loaded with vapor loses its capacity to travel rapidly toward the ground, and becomes tangled in the body of the cloud, so that the negative charges tend to accumulate on the bottom while the positive charges congregate on the tops of the clouds. This separation of positive and negative electricity on the upper and the lower surface of clouds always exists, and it may grow to many thousand volts per meter, so that finally the insulating strength of the air is broken down and a lightning discharge takes place. Evaporation of aqueous vapor carrying upward negative ions from the earth by the ascensional force of the air may increase the negative electricity on the lower surface of clouds. When drops of rain fall some negative electricity returns to the ground, but it is not a very large quantity. The action of the wind disturbs the travel of the ions along the lines of electrostatic force toward their opposite charges. The many complex conditions at the earth, the distribution of vegetation, surface masses, charges on the ground, on buildings, near waterfalls, the variations due to the smoke of cities, mechanical electric currents, and a thousand other circumstances make the observations on atmospheric electricity difficult, and the results more uncertain and unsteady than in any other meteorological element. The local circumstances so far tend to disturb the average general distribution of electricity that it is not an element suited to observations with the purpose of providing a reliable basis for forecasting. As is well known this element is much less valuable than the magnetic field surrounding the earth for that object, because the latter transmits pulsations which embrace synchronously the entire earth, and it also has a distinct connection with the solar activity, which is the primary source of the energy.

THE CONDUCTIVITY OF THE ATMOSPHERE AS MEASURED BY EXPERIMENTS.

A series of careful experiments were first made by **Linns** (Meteorol. Zeit., 1887, p. 352) to determine the rate of dissipation of charges of electricity in free air, the charge being maintained at a constant potential. The result was that about one hundred minutes were required for a charge to dissipate itself. This is interpreted to mean that pure dry air has a very slight degree of electrical conductivity. These experiments have been repeated by **Elster** and **Geitel** (Terr. Mag., Dec., 1899) with improved apparatus, and in various localities, in order to find the influence of the place upon the rate of dissipation. Table 24 collects these results, and gives in the first column the locality and the kind of place, as mountain peak or valley, lowland, near falling water; the second and third columns contain the percentage of loss per minute for positive and negative charges, respectively; the fourth and fifth columns, the corresponding minutes required to dissipate a charge.

Table 24.—*Rate of dissipation of positive and negative charges of electricity maintained at a constant potential.*

ELSTER AND GEITEL.—CLEAR WEATHER DISSIPATION.

Stations	Percentage of loss per minute		Time for the loss of the total charge	
	Positive	Negative	Positive	Negative
Lowlands	0.4	2.6	250	39
Brocken Peak, 1140 m.	1.4	2.6	71	39
Santis Peak, 2500 m.	6.2	6.7	16	15
	2.0	6.9	50	14
	1.9	8.3	52	12
Termatt Valley, 1620 m.	4.5	4.4	22	22
Riffelhauses Plain, 2600 m.	4.4	6.8	22	15
Gornergratbahn Pass, 3000 m.	2.7	7.0	37	14
Gornergrats Peak, 3140 m.	0.7	6.6	143	15
Termatt base of waterfall	16.2	1.9	6	52
Small room	0.7	0.7	143	143

It is seen that negative electricity dissipates faster than positive, especially on mountain peaks, where it may assume almost a unipolar type. In mountain valleys the rate is more nearly equal for each electricity, also in small rooms, but near the base of a waterfall the positive dissipates so much faster than negative as to become unipolar of the opposite type to mountain peaks. Hence it is concluded that mountain peaks are rich in positive ions, and the localities at the foot of waterfalls are equally abundant in negative electricity. The dissipation is explained by the fact that the ions in the upper air seek the earth along the lines of electric force, the positive accumulating on the mountains and the negative in the valleys, by these physical processes. It was found that the force of the wind has little to do with the rate of dissipation; that the presence of clouds, mist, and other causes of obscuration of the sky greatly retards dissipation, because the ions become entangled in the cloud and are not free to move to the ends of electrostatic lines, where the charges can be neutralized. The rate of dissipation is smaller in winter than in summer; smaller in the morning than at night. Cloud building in negatively ionized air takes place at lower pressure and warmer temperature than in positively ionized air, so that cyclones are associated with negative ions and anticyclones with positive ions. The cloud itself is a mixture of dry air containing positive ions and water drops containing negative ions, and therefore falling drops leave positive ions remaining in the air. The diurnal and yearly periods of atmospheric electricity are very closely connected with these processes. Positive potential fall is the rule and a negative gradient the exception, this latter being difficult to account for at all on the ionization theory.

H. Ebert, at Munich, Germany, on June 30, November 10, 1900, and January 17, 1901, made balloon ascensions to about 3,000 or 4,000 meters, and carried the Elster-Geitel form of apparatus for measuring the rate of dissipation of electricity from a charged body. He found that this was an entirely practical procedure and obtained important and interesting results bearing on the ionization and conductivity of the air.

Examples.

November 10, 1900			January 17, 1901			
Height	Rate of dissipation		Height	Rate of dissipation		
Meters			*Meters*			
1975	$a_+=1.16\%$	$q=1.81$	995	$a_+=0.41\%$	$q=4.58$	
2160	$a_-=2.10$		1275	$a_-=1.89$		
2275	$a_-=2.29$	$q=1.28$	1470	$a_+=4.01$	$q=2.18$	Cage was used
2420	$a_+=1.79$		1550	$a_-=9.53$		
2890	$a_+=1.17$	$q=1.40$	1930	$a_+=1.03$	$q=2.07$	
2965	$a_-=1.63$		2285	$a_-=2.13$		
3400	$a_+=2.50$	$q=1.10$	2375	$a_+=13.86$	$q=1.08$	Cage was used
3705	$a_-=2.75$		2560	$a_+=11.04$		
3710	$a_-=2.76$	$q=0.93$	2880	$a_-=12.16$		
3770	$a_+=2.96$		2930	$a_-=17.48$		
			3005	$a_-=14.03$		
			3105	$a_+=1.02$	$q=5.10$	
			3060	$a_-=5.20$		

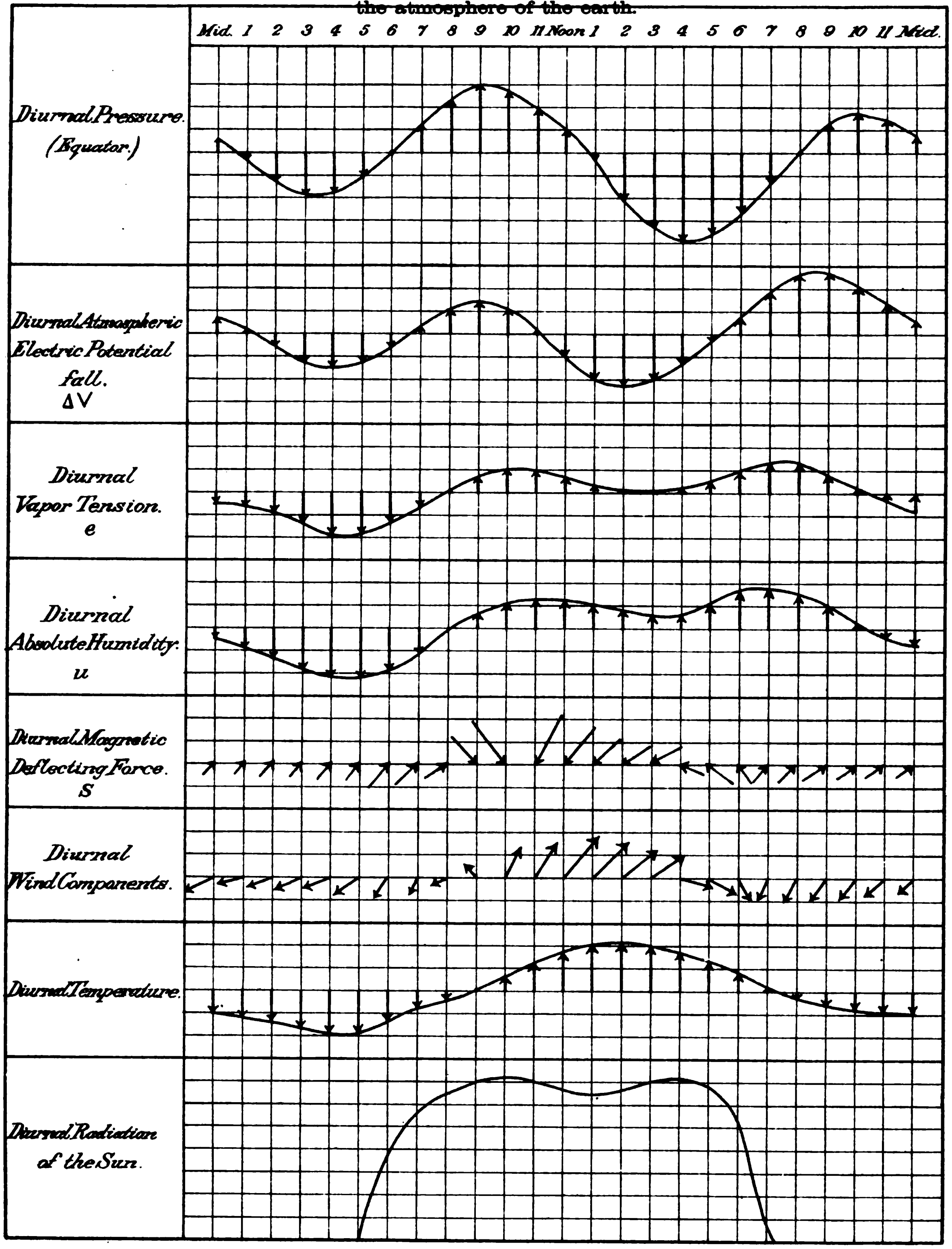
a_+=the percentage of loss of the original positive charge maintained at a constant potential per minute; a_-=the same for the negative charge. $q=\frac{a_-}{a_+}$, the ratio of the negative to the positive rate. An inspection of the examples of November 10, 1900, and January 17, 1901, shows that generally there is a unipolar type at the ground, where the negative sign preponderates, and that the positive and negative rates become about equal in the neighborhood of 3,000 meters. The values of a_+ and a_- tend to become larger with the altitude, though the irregularity in the data does not permit a sure deduction from these few measurements. Interpreted in the language of ions, the negative ions are in excess at the ground, but become equal to the positive at about 3,000 meters, so that this is probably the region of special activity of ionization in the atmosphere. The conductivity of the air increases upward; the number and the activity of movement of the ions shows that it becomes greater in the strata of less pressure. The increase of the values of a_+ and a_-, wherever the ion catch-cage was used, is shown by the large values obtained in the ascension of January 17, 1901. This method permits more rápid readings, a new one every five minutes, and thus quick measures of the electric condition of thin strata. The electric and the meteorological conditions change suddenly at different levels whenever there is passage from one overlying stratum to another. The atmosphere is very strongly stratified by currents of different constitution and the electricity follows this discontinuity, so that general laws do not usually prevail in a particular ascension without very marked exceptions. All this is in conformity with the ionization theory of the origin of atmospheric electricity, and it justifies the continuance of such observations by means of balloons.

According to the above experiments, a positive charge in free clear air dissipates in about seventy-five minutes, and a negative in about twenty-five minutes, and the rate of negative dissipation is three times as fast as that of the positive. If the earth gives up its negative charge to the air at this rate it would mean that an exceedingly vigorous source of supply must be continuously in action to recharge it. However, the important conclusion for our main purpose is the establishment of the fact that the *coefficient of conductivity in free air is so very small that the magnetic induction to be derived from true conduction currents is insignificant.* Also, that the theories of terrestrial magnetism depending on electric currents in the atmosphere must be excluded except for a shallow stratum of very highly rarefied air near the upper boundary of it. Further evidence of its efficiency in generating electric currents than we now possess must be obtained before it can be admitted to account for the comparatively large magnetic forces which are measured at the earth's surface.

THE DISTRIBUTION AND THE DIURNAL VARIATION OF ENERGY IN THE EARTH'S ATMOSPHERE.

We will now proceed to a more specific summary of the facts regarding the distribution and the variation of energy in the atmosphere, as expressed in the diurnal changes of pressure, vapor tension, and absolute humidity, electric potential fall, temperature, magnetic deflecting forces, and diurnal wind components. The diurnal periods of all these elements except perhaps the temperature have been a source of perplexity to meteorologists, so that all possible information regarding their connection with solar radiation is important and valuable. The curves or the vectors denoting the variations on the daily mean at the several hours of the day are compiled from readily accessible data, and as less stress is to be laid upon the magnitude of the deflection than upon the laws of the mean distribution, the discussion will be carried on in general terms. A quantitative analysis of these interdependent elements is in progress, but the result is not yet available. The curves on Chart 29 of the diurnal pressure at the equator, and the wind components are taken from the International Cloud Report, pages 466, 476; that of the diurnal atmospheric electric potential fall or gradient is compiled from observations made at 17 different stations, including MENDENHALL's series in the United States, Greenwich, Perpignon, Batavia, Paris, etc.; that of the diurnal magnetic deflecting forces, from Bulletin 21, Table 19, for middle latitudes; the temperature from Weather Bureau data; those of the diurnal vapor pressure and absolute humidity from the report on the barometry of the United States, Volume II, Annual Report Chief Weather Bureau, 1900–1901, and comprise the mean result from 234 stations. The diurnal radiation of the sun in calories per square centimeter per minute is taken from HANN's Meteorologie, page 38. An inspection of these curves shows conclusively that the *diurnal pressure, vapor tension, and electric potential variation are of the same type*, and hence it is proper

CHART 29. Diurnal variations of the meteorological, electrical, and magnetic elements in the atmosphere of the earth.



to infer that they all must be referred to the same cause. The magnetic force *s* and the wind components are evidently vector systems, not only related together, but practically identical, except that the direction of the magnetic vectors are the reverse of the wind components. The temperature curve has the same trend as the first group during the night, but it is not reversed from about 10 a. m. to 7 p. m. during the day. This is readily seen by comparing the temperature and the vapor tension curves. If the vapor tension curve were to complete its crest, then the temperature type with one maximum and minimum would be reproduced. It is believed that the true type curve is that of the temperature, but it seems to be disturbed in the other elements by superposing upon it a reversal during the midday and afternoon, as if the physical process which progresses in the forenoon hours of the day were arrested and reversed during the warmest part of the day. The radiation curve shows a similar midday reversal of activity, and at the surface of the earth there is less heat received than during the hottest portion of the day. It is known that the double diurnal period in the pressure, electrical potential and vapor tension becomes a single period at a distance of 1,000 to 3,000 meters above the ground, so that the inversion is confined to the lower strata. Dr. HANN discusses this phenomenon only a little, but associates the variation with the diathermacy and absorption of the atmosphere. The physical questions involved are very difficult to settle because of the lack of suitable observations throughout the gaseous envelope of the earth. These several terms no doubt indicate the effect of the absorption of the solar energy in the air. It is especially to be remarked that these diurnal changes all begin promptly with the commencement of the morning radiation; they rise to a maximum before noon in all cases except that of the temperature, which continues to increase till about 2 p. m. It seems as if the pressure, and the electric potential, start in a wave about 10 a. m., and that the secondary evening wave may be in some way reflected from it by simple reaction. The morning wave is so distinctly connected with the rise in radiation that it must be regarded as the real thing to first explain, expecting that the evening wave will find its cause in a rebound from the other. We shall venture some further remarks on this obscure subject. Thus, if the dissociation of atoms by ionization, as indicated in the electric potential curve, proceeds most rapidly at 9 a. m. and 9 p. m., it has in some way been hindered so that even a recombination goes on during the afternoon and later at night. In the same way, if the pressure increases till 9 a. m. to a maximum it is arrested and a minimum occurs in the afternoon, but it is resumed in the evening. The same may be said of the vapor tension. I shall suggest that the formation of ions and their redistribution by the more rapid movement of the negative charges to earth leaves a maximum of positive ions in the air at 9 a. m. and 9 p. m. Since these are of the same sign and associated with the particles of air, there must be electric repulsion between them, and no doubt other physical forces, acting to produce a similar effect. But with the increase of heat at midday and the ascensional movement from the ground of negatively charged masses, dust and other small particles, rather than ions, by the buoyancy of the air derived from the surface heating, there is caused the well-known diurnal convection, through which the negative charges are returned to the upper layers; then recombination of the ions occurs, and the repulsive forces are neutralized, so that there is a fall in the dry air and vapor pressures. An attempt will be made to establish this proposition quantitatively in the future, being content now with pointing out that the movement is in the right direction at all parts of the day, though the evening wave is more difficult to understand. This is in harmony with my discussion in Chapter 9 of the International Cloud Report, which does not accept the validity of the thermic theory nor the forced oscillation theory, but does refer the action to a static attraction or repulsion there summarized as magnetic attraction. It may be noted that nearly all my work has resulted in an apparently necessary endeavor to refer these remarkable phenomena back to a system of forces acting statically *in situ*, rather than to dynamic currents, either of the circulation of the air or electricity.

Finally, it is shown on the 30-inch globe of deflecting magnetic vectors described in Bulletin No. 21 that there are in the middle latitudes two turning points in their direction, such that they point generally eastward from 7 p. m. to 10 a. m. and westward from 11 a. m. to 6 p. m. An attempt is made on Chart 29 to indicate the vertical directions by printing downward vectors in red ink and upward vectors in black ink. These two turning points are distributed symmetrically to the maxima of the vapor tension curve, and hence to all the other curves of the system more or less exactly. The strength of the deflecting magnetic vectors varies greatly in different latitudes, as shown on Chart 30, so that one should not draw too rigid conclusions from the length of the vectors, but should also consider the positions of their turning points. The first row of vectors pertains to the north polar belt which terminates at latitude 60°; the second to the north temperate belt which terminates at latitude 30°; the third to the tropical belt which extends from 30° north to 30° south; the fourth to the south temperate which ends in latitude 60° south; the fifth to the south polar belt, which is of course conjectural. Dr. H. Fritsche has recently discussed the diurnal deflecting vectors from the point of view of the Gaussian Potential Theory, finds a similar distribution, and concludes that they can not be caused by a potential inside or outside the earth, but that electric currents might do the work if they can be accounted for by suitable physical processes.* These belts are bounded in latitude by the disappearance of the vertical component, and this is accompanied by a sudden change in the direction. Generally speaking, there is a marked system of disturbances in longitude at the 9 a. m. and the 9 p. m. hours, which corresponds very closely with the maxima of the diurnal pressure, the atmospheric electricity, and the vapor curves. This remarkable parallelism between the several elements, therefore, suggests that the explanation is to be found in those changes produced *in situ* in the atmosphere by the action of solar radiation upon its constituents, of which ionization is one important manifestation. This transformation of energy, as expressed in the common meteorological elements, in atmospheric electricity and magnetism, renders the entire subject of the physical conditions and the partially understood laws which govern them of especial importance and interest to meteorologists. One can not fail to note that the diurnal magnetic system is marked off approximately by the same parallels of latitude, namely: 30° and 70°, which divide up the atmospheric circulation into the well-known belts, tropical, temperate, and polar.

THE VARIATION OF THE METEOROLOGICAL, MAGNETIC. AND ELECTRICAL FORCES IN LATITUDE.

There is yet another branch of the subject of the relation of the magnetic vectors and the electric potential to the meteorological elements, which will be introduced by referring to several other papers on these topics, namely, those concerned with the variation in latitude of the vectors expressing the changes in longer intervals of time than the diurnal period. In the Amer. Journ. Sci., August, 1895, I published a paper on The Earth a Magnetic Shell, showing the results of a computation on the vectors which are superposed upon the normal magnetic field at 26 stations, varying in magnetic latitude from Kingua Fjord +78° to Hobarton −55°. This was explained fully in Bulletin No. 21, and Table 25, Section I, is reproduced from it. Under the mean values are given the elements of the vectors, collected according as the direction is southward or northward, respectively. If the diurnal values for $H . D . V .$ are plotted on a base line, so that the curve covers many days, the variations $-\Delta H$ from the mean indicate that the curve of the horizontal force is deflected below the line, and $+\Delta H$ above it; $-\Delta D$ to the eastward and $+\Delta D$ to the westward of the magnetic meridian; $-\Delta V$ upward in the northern hemisphere and $+\Delta V$ downward. Combine these rectangular coordinates into equivalent polar coordinates, so that $s=$ the total deflecting vector, $\sigma=$ its horizontal trace, $\alpha=$ the angle that s makes with σ, and $\beta=$ the angle that σ makes with the magnetic meridian, where $\beta=0°$ is northward, $\beta=180°$ is southward. The several stations were computed for all variations throughout a single year, and the resulting angle β is so close to the magnetic meridian as to satisfy the theoretical condition that an external field produces no east-west component. The vectors were slightly adjusted as to length by graphical construction, as indicated; the angle α was computed from $(\sigma . s)$ because the mean of the α angles is much less correct, as explained in the text of W. B. Bulletin No. 21.

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*Die Tägliche Periode der Erdmagnetischen Elementen, von Dr. H. Fritsche, St. Petersburg, 1902.

CHART 30. Typical vectors of the magnetic deflecting force in the principal diurnal belts.

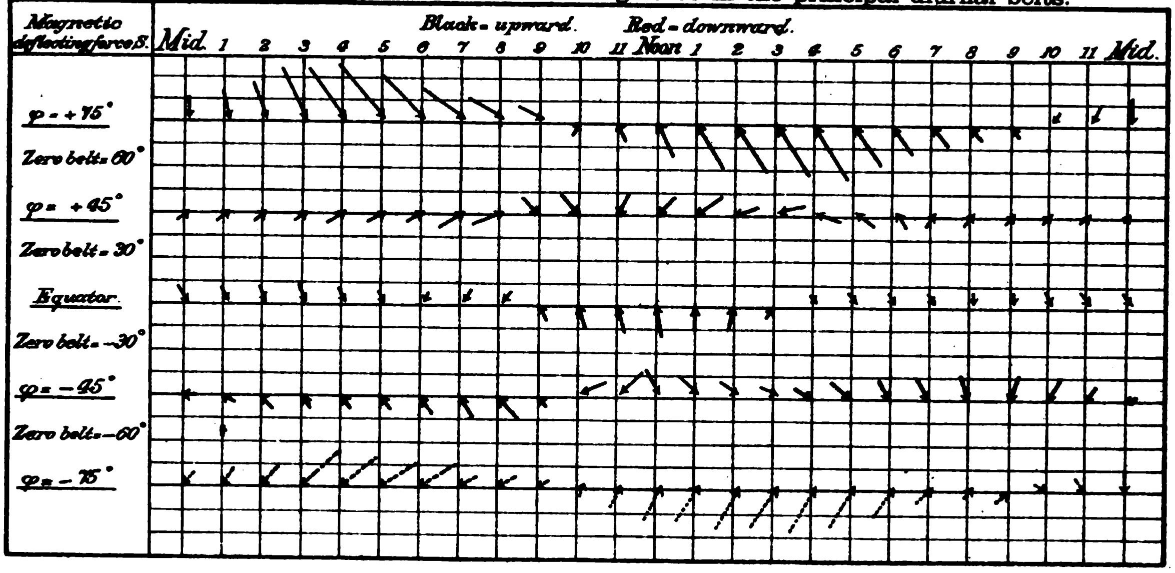

TABLE 25.—*The mean deflecting magnetic vector s at 26 stations distributed widely in latitude.*

[F. H. BIGELOW in Amer. Journ. Sci., August, 1895.]

I.

No	Station	Magnetic latitude	Year	Mean values								Adjusted values					
				South				North				South			North		
				β	α	s	σ	β	α	s	σ	s	σ	α	s	σ	α
		°												°			
1	Kingua Fjord	77.9	1882	161	+ 5	45	27	337	− 6	37	23	45	28	54	38	23	54
2	Fort Rae	76.0	1882	190	+ 8	46	30	5	− 8	39	22	53	29	55	43	24	55
3	Point Barrow	73.1	1882	180	− 6	59	29	4	+ 5	55	29	60	30	58	52	24	58
4	Cap Thordsen	71.1	1882	186	−14	62	28	6	+ 8	50	23	59	30	59	52	23	59
5	Jan Mayen	68.8	1882	180	+10	54	29	4	− 9	44	22	55	27	60	49	22	60
6	Bossekop	64.4	1882	188	+14	43	29	18	− 6	33	19	42	23	58	33	17	58
7	Toronto	62.2	1847	176	−28	32	18	356	+27	25	11	34	18	55	26	13	55
8	Sodankyla	61.4	1882	184	+ 5	16	15	14	− 2	14	12	31	15	54	24	11	54
9	Washington	55.6	1890	179	+19	18	7	357	0	20	8	20	12	48	14	8	48
10	Pawlowsk	55.1	1882	196	+10	12	10	15	− 9	10	8	18	10	47	13	8	47
11	Greenwich	50.4	1887	175	− 6	13	9	359	+ 1	13	9	14	9	43	10	7	43
12	Parc St. Maur	47.3	1884	177	+ 2	12	9	357	− 4	11	8	13	10	41	10	8	41
13	Vienna	44.8	1882	178	+ 5	19	15	1	− 1	20	16	14	11	40	11	9	40
14	Pola	41.7	1892	183	+14	23	16	1	− 6	17	11	16	12	38	12	9	38
15	Los Angeles	40.3	1883	181	+10	22	12	0	− 8	23	10	17	13	37	13	10	37
16	Tiflis	36.1	1882	182	+ 6	15	12	13	− 7	13	11	23	19	37	17	16	37
17	Zi-ka-wei	27.6	1882	187	− 4	42	32	351	+ 5	33	23	38	27	43	32	23	43
18	Bombay	9.9	1863	182	+ 4	36	20	3	− 5	33	16	31	20	53	25	15	53
19	Madras	3.8	1855	185	+ 2	13	11	349	− 1	12	10	19	14	36	15	11	36
20	Singapore	− 6.4	1845	182	− 2	14	11	359	− 8	12	10	15	11	39	11	8	39
21	St. Helena	−11.2	1843	178	−10	17	9	349	− 2	17	8	16	10	57	12	7	57
22	Batavia	−15.1	1890	182	+13	16	8	1	−12	16	9	22	12	58	15	8	58
23	Süd Georgien	−29.8	1882	187	+26	52	20	8	−17	47	15	36	19	47	31	16	47
24	Cape Horn	−33.5	1882	176	− 2	15	13	6	+ 4	13	10	25	13	44	19	10	44
25	Cape Good Hope	−33.9	1842	185	+16	19	11	353	− 3	16	11	20	12	43	15	9	43
26	Hobarton	−54.8	1842	176	+22	26	15	0	−27	22	13	26	14	52	22	12	52

β=magnetic azimuth, for north=0°, west=90°, south=180°, east=270°.

II. COMPARISON OF THE AZIMUTH ANGLES β AS COMPUTED BY BIGELOW AND VAN BEMMELEN.

Station.	β_S	$\Delta\beta_S$	β_N	$\Delta\beta_N$	Mean	β	Dec.	Bigelow β'_1	Bemm. β'_2	Difference $\beta'_2-\beta'_1$
Kingua Fjord	161	−19	337	−23	−21	159	N 72 W	231	207	−24
Fort Rae	190	+10	5	+ 5	+ 8	188	N 40 E	148	184	+36
Point Barrow	180	0	4	+ 4	+ 2	182	N 36 E	146	156	+10
Cap Thordsen	186	+ 6	6	+ 6	+ 6	186	N 13 W	199	220	+21
Jan Mayen	180	0	4	+ 4	+ 2	182	N 30 W	212	222	+10
Bossekop	188	+ 8	18	+18	+13	193	N 4 W	197	205	+ 8
Toronto	176	− 4	356	− 4	− 4	176	N 1 W	177	181	+ 4
Sodankyla	184	+ 4	14	+14	+ 9	189	N 1 W	190	198	+ 8
Washington	179	− 1	357	− 3	− 2	178	N 4 W	182	187	+ 5
Pawlowsk	196	+16	15	+15	+16	196	N 1 W	197	200	+ 3
Greenwich	175	− 5	359	− 1	− 3	177	N 18 W	195	198	+ 3
Parc St. Maur	177	− 3	357	− 3	− 3	177	....	....	....	....
Vienna	178	− 2	1	+ 1	− 1	179	....	....	....	....
Pola	183	+ 3	1	+ 1	+ 2	182	N 10 W	192	188	− 4
Los Angeles	181	+ 1	0	0	+ 1	181	....	....	....	....
Tiflis	182	+ 2	13	+13	+ 8	188	N 1 E	187	195	+ 8
Zi-ka-wei	187	+ 7	351	− 9	− 1	179	N 2 W	181	174	− 7
Bombay	182	+ 2	3	+ 3	+ 2	182	N 1 E	181	188	+ 7
Madras	185	+ 5	349	−11	− 3	177	....	....	....	....
Singapore	182	+ 2	359	− 1	+ 1	181	....	....	....	....
St. Helena	178	− 2	349	−11	− 7	173	N 23 W	196	168	−28
Batavia	182	+ 2	1	+ 1	+ 2	182	....	....	....	....
Süd Georgien	187	+ 7	8	+ 8	+ 8	188	N 0 W	188	188	0
Cape Horn	176	− 4	6	+ 6	+ 1	181	N 20 E	161	192	+31
Cape Good Hope	185	+ 5	353	− 7	− 1	179	N 29 W	208	167	−41
Hobarton	176	− 4	0	0	− 2	178	N 10 E	168	168	0

The second section of Table 25, "comparison of the azimuth angles β as computed by Bigelow and Van Bemmelen," gives a summary of a paper by Van Bemmelen in Terrestrial Magnetism, September, 1900, on "The magnetic post purturbation and the current vortices of Schmidt." The geographical azimuth (β'_2) of the disturbing force at 28 stations is given, and these were computed from the large disturbances of selected days. In my table β is the magnetic azimuth and β' the geographical azimuth of the deflecting vector; β_S is the southward and β_N the northward value from the first section of the table; $\Delta\beta_S$ and $\Delta\beta_N$ are the differences between the magnetic and the line of 0°–180° azimuths; from the mean $=\frac{1}{2}(\Delta\beta_S+\Delta\beta_N)$ the average magnetic azimuth β is found. The declination is taken from Table 17, Bulletin No. 21, page 84, and the geographical azimuth β'_1 (Bigelow) is computed. The next column β'_2 (Bemmelen) contains his geographical azimuth. The difference $\beta'_2-\beta'_1$ shows that the two computations are in close agreement except for a few polar stations. This may arise from the fact that we have not employed the same data in the discussion, since my computations depend upon all the variations at the several stations throughout a year, and his upon the days of special disturbances. We conclude that the disturbing vectors cling closely to the magnetic meridians, and that the east-west component is very small. If Van Bemmelen should in a similar manner extend his computation to include the vertical force in the vector, we could then compare his result with the other values in the upper section of Table 25, or with Chart 10 of Bulletin No. 21. It is very desirable that other magneticians should construct such deflecting vectors for the different magnetic fields as was done in that report.

The adjusted vectors, Table 25, Section I, are plotted on figure 2, Chart 31, and they make a

CHART 31.

Comparisons of the magnetic and electric vectors in latitude.

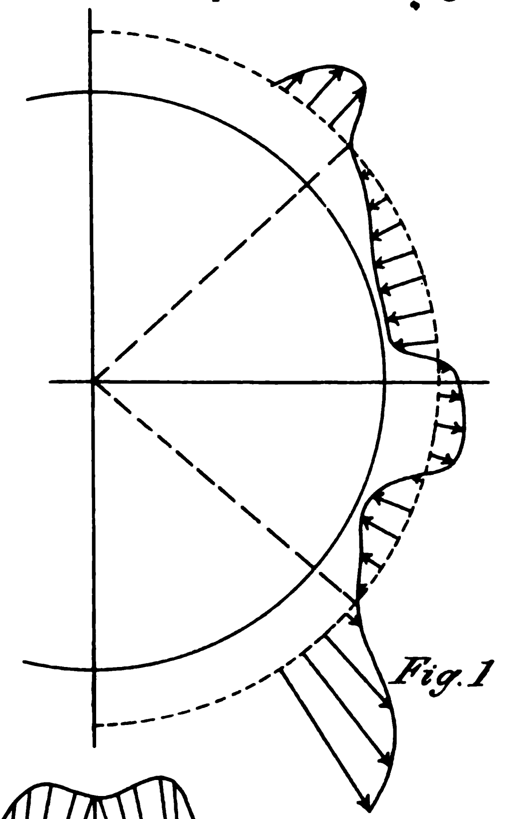

Fig. 1

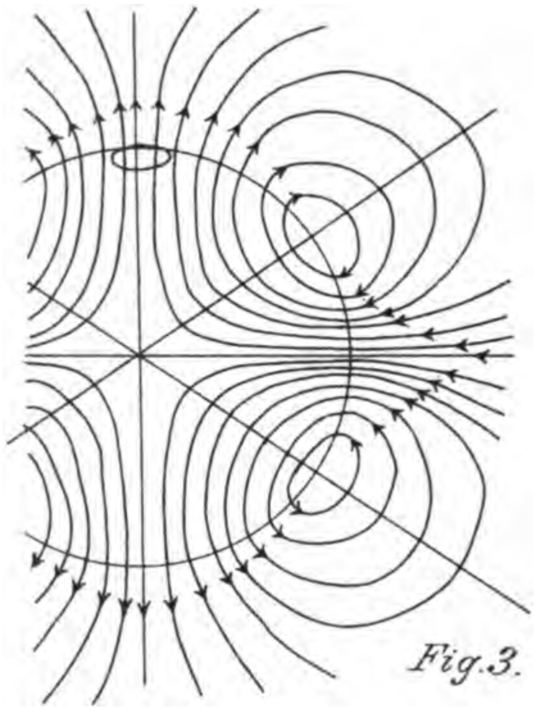

Fig. 3.

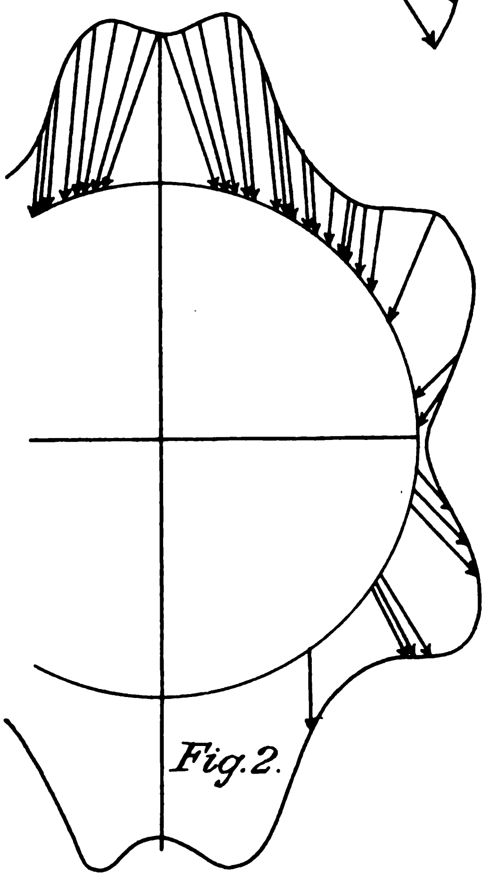

Fig. 2.

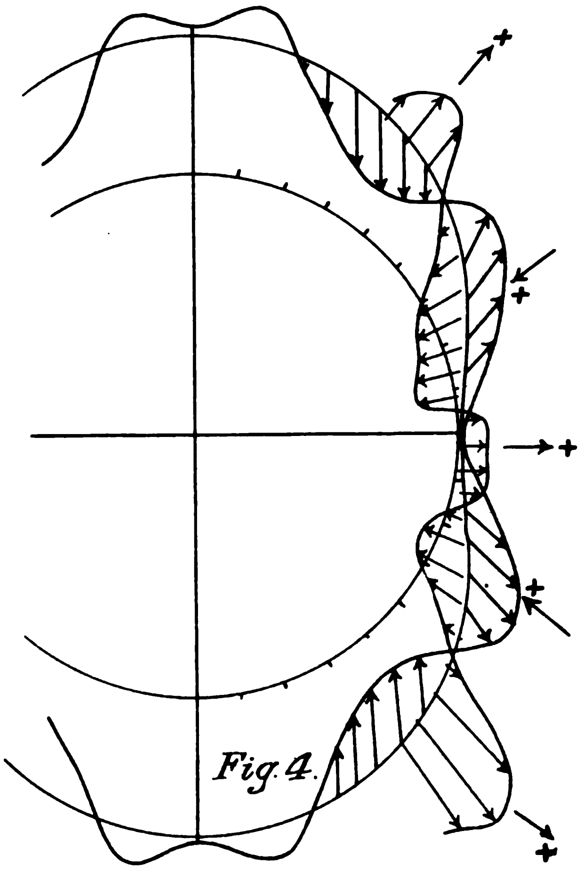

Fig. 4.

curve of intensity giving maxima at latitude 30° and 80°. This evidently differs from the theoretical intensity belonging to the distribution of force for a permeable sphere placed in an external field. The direction of the vectors was explained by assuming that the earth too acts like a permeable shell (pp. 70–71), and the theoretical diagram matches the computed vector directions so closely as to give occasion to further remark in this place. The intensity of the vector system has been noted by Professor SCHUSTER to differ from the theoretical form, and he infers that this is an argument against the general theorem to which I ascribed the phenomenon. However, by computing the normal magnetic curve from the formulæ given in Table 26, "The relative intensity of the magnetic force induced on a permeable sphere or shell when immersed in an external field," we have the curve shown in the noninflected curve of Chart 31, figure 4. This computed system is superposed upon the vector system derived from the observations, and gives the comparison of the computed and observed vectors in latitude. The differences between these two vector systems consist of residuals in which the normal field shows an excess over the observed field from near the pole to about latitude 40°, and a defect between latitude 40° and the equator, the same being true in both hemispheres. Any physical principles which account for the superposition of these secondary or residual magnetic vectors upon the primary vectors produced by placing the earth as a magnetic sphere, positive pole in the southern hemisphere and negative pole in the northern hemisphere, within the sun's external magnetic field, positive on the northern side of the eliptic and negative on the southern side of the eliptic, are competent to remove this objection against the theory advanced to account for the phenomenon Hence it would follow that if there is reason for the existence of this secondary field as a disturbance, its superposition upon the normal external field, so far from being an argument against the sun's magnetism, as was assumed, becomes very powerful evidence in its favor. Indeed, it seems to me that this feature of the magnetic field at the earth, taken in connection with the phenomenon of the stripping of the polar regions of the sun of all coronal rays, constitutes nearly a proof

TABLE 26.—*Relative intensity of the magnetic force induced on a permeable sphere or shell when immersed in an external field.*

[Formulæ—Bulletin 21, p. 67.]

$$F_n = X\cos\theta + Y\sin\theta = \frac{4}{3}\pi R^3 I\cdot\frac{2\cos\theta}{r^3} = \frac{4}{3}\pi R^3 I\frac{2x}{r^4} = -F_i\frac{R^3}{r^3}\cdot 2\cos\theta = \frac{4}{3}\pi I\cdot 2\cos\theta$$

$$F_t = -X\sin\theta + Y\cos\theta = \frac{4}{3}\pi R^3 I\cdot\frac{\sin\theta}{r^3} = \frac{4}{3}\pi R^3 I\frac{y}{r^4} = -F_i\frac{R^3}{r^3}\cdot\sin\theta = \frac{4}{3}\pi I\cdot\sin\theta$$

For the surface $R=r$ $\quad -F_i=\frac{4}{3}\pi\,.\,I$ $\quad$ Assume for type, $\frac{4}{3}\pi\,I=$unity.

Polar distance	$2\cos\theta$ $=F_n$	$\sin\theta$ $=F_t$	$\tan\alpha$ $=\frac{F_n}{F_t}$	α	$\left(F_n^2+F_t^2\right)^{\frac{1}{2}}$ $=F$	s
$\theta=0$	2.0000	0.0000	∞	90.0°	2.00	.00040
10	1.9696	0.1736	11.30	85.0	1.98	40
20	1.8794	0.3420	5.49	79.7	1.91	38
30	1.7320	0.5000	3.46	73.9	1.80	36
40	1.5320	0.6428	2.38	67.2	1.66	33
50	1.2856	0.7660	1.68	59.3	1.50	30
60	1.0000	0.8660	1.16	49.3	1.32	26
70	0.6840	0.9397	0.73	36.2	1.16	23
80	0.3472	0.9848	0.35	19.3	1.05	21
90	0.0000	1.0000	0.00	0.0	1.00	.00020

positive that the sun is a strongly magnetized sphere, as supposed in my original report. The maximum strength of this secondary field at latitude 60° is 0.00020 C. G. S., and at latitude 30° it is 0.00015 C. G. S. There is a slight maximum near the pole in the region of the middle of the auroral belt, which I shall neglect for the sake of not complicating the main purpose of this inquiry.

TABLE 27.—*Vertical earth-air electric currents.*

[L. A. BAUER, Terr. Mag., March, 1897.]

+ = upward electric current; — = downward.

Units	ΣY_e C. G. S.		I 10000 amp.		ΔI 10000 amp.		i 1 amp. per sq. km.			i C. G. S.
Latitude	N	S	N	S	N	S	N	S	Mean	Mean
60	+.0271	+.0992	+ 60	+219						
					+ 42	+326	+.035	+.274	+.154	+.01540
55	+.0401	—.0422	+102	—107						
					+141	+303	+.104	+.224	+.164	+.01640
50	+.0856	—.1445	+243	—410						
					+135	+238	+.091	+.159	+.125	+.01250
45	+.1213	—.2078	+378	—648						
					— 20	+ 37	—.012	+.023	+.006	+.00060
40	+.1057	—.2022	+358	—685						
					— 32	— 39	—.018	—.022	—.020	—.00200
35	+.0900	—.1784	+326	—646						
					— 66	— 76	—.035	—.040	—.038	—.00380
30	+.0680	—.1489	+260	—570						
					—118	—151	—.060	—.077	—.068	—.00680
25	+.0381	—.1048	+142	—419						
					—132	—175	—.064	—.085	—.074	—.00740
20	+.0023	—.0587	+ 10	—244						
					—166	— 64	—.079	—.030	—.054	—.00540
15	—.0366	—.0422	—156	—180						
					—155	+ 58	—.072	+.027	—.022	—.00220
10	—.0714	—.0547	—311	—238						
					—185	+ 97	—.084	+.044	—.020	—.00200
5	—.1128	—.0762	—496	—335						
					+ 79	+ 82	+.136	+.037	+.036	+.00360
Equator 0	—.0944	—.0944	—417	—417						.00160

L. A. BAUER published in Terrestrial Magnetism, March, 1897, an account of his research into the line integral of the magnetic force along the parallels of latitude, at 5° intervals, the components being ultimately derived from NEUMAYER's Charts. He recognizes the possible imperfections inherent in such data, and yet reaches a result so symmetrically disposed as to suggest interesting physical conditions in the earth's magnetic field. Table 28 is taken from Dr. BAUER's paper, and, together with figure 1, Chart 31, shows the result. $\Sigma Y_e = \Sigma H \cos \varepsilon =$ the summation of the easterly components, as constructed for each degree of longitude; $I=$the resultant or the total quantity of electricity passing in the unit time, perpendicular to the surface of the earth, through the zone between the parallel of latitude and the pole, expressed in units of 10,000 ampères; $\Delta I=$the part in the narrow zones 5° wide; $i=$the corresponding electric vertical earth-air current in amperes per square kilometer; the last column gives the mean value of i in C. G. S. electro-magnetic units. For the sake of comparison with the magnetic secondary vectors, the electric vectors of figure 1 are plotted on the mean magnetic curve of the primary field in figure 4, Chart 31, and they are shown in red. It is noted that they agree in representing a very similar distribution of force, though of course not comparable with each other superficially, since the black secondary vectors represent magnetic force and the red vectors electric current. The turning points and the location of the maxima are nearly identical, except that BAUER has some small vertical currents just south of the equator. This approximate agreement of two systems of forces can hardly be considered accidental, and it gives ground for believing that each of them stands for physical realities.

In order to consider the proper mode of explaining the existence of these two vector systems, I shall introduce a few extracts from papers dealing with the question. Dr. AD. SCHMIDT's conclusion regarding his computation on the terrestrial magnetic field is well known to be as follows (Neue Berechnung des Erdmagnetischen Potentials, 1895):

> The empirically determined distribution of the earth's magnetic force at the surface, as it is represented by Dr. NEUMAYER's charts for the epoch 1885.0, depends for the most part upon causes which have their seat within the earth, but it can not be exclusively referred to such. A small part of the force, about one-fortieth of the whole amount, is to be ascribed to sources outside the earth's surface; another, somewhat larger part, which is equivalent to a current of about one-sixth ampère on an area of 1 square kilometer, should be referred to electric currents which traverse this surface.

The first and second components have a potential, while the third has no potential, but is assumed to be induced by electric currents. Dr. BAUER refers his vectors to a closed system of electric currents, such as HERTZ deduces for a magnetic sphere rotating in a conducting medium. The proposition as stated by HERTZ is as follows (H. Hertz, Induction in Rotating Spheres, "Miscellaneous papers," p. 107):

> When a sphere of any arbitrary magnetic properties rotates in a liquid, which is itself a conductor, and makes electric contact with the surface of the sphere, the sphere will induce currents in the liquid. In general these no longer flow in concentric shells, but traverse the magnet. The form of the lines of flow does not depend upon the resistances of the magnet and the liquid. But the intensity vanishes when either resistance becomes infinitely great.

L. A. BAUER (Terr. Mag., March, 1897) comments as follows:

> (Page 17:) In their general nature, it will be seen that the currents resemble the electric currents resulting from the rotation of a magnetic sphere in a conducting fluid.
>
> (Page 20:) For the present, then, and until further investigations are made, it is useless to ask ourselves the question whether the vertical currents are the result of the rotation of the magnetized earth, with reference to the ether outside, or whether they are due to the differential rotation of the earth and atmosphere which takes place in consequence of the huge atmospheric whirls about each pole.

Prof. A. SCHUSTER (Terr. Mag., January, 1896) had already remarked:

> (Page 12:) It is seen that it would take 125 centuries to lengthen the day by 1 second. Small as this effect seems to be, it could not have escaped the notice of astronomers, for the earth as a timekeeper would lose 2.6 minutes in a century. This would limit us to a possible couple about six times smaller than the maximum, and hence if space had a conductivity either smaller than 5×10^{-16} or greater than 10^{-11} the effects as regards the lengthening of the day would be inappreciable.
>
> (Page 13:) Our calculation has proceeded on the assumption of a uniform conductivity of space. The reactions must always be such as to cause an induced potential displaced in the direction of rotation as compared to the inducing one.
>
> (Page 14:) The combined effect will be a tendency to shift the magnetic axis, in a direction opposite that of a sphere's rotation, round the axis of rotation and at the same time toward it. In whatever way the sphere was originally magnetized, the magnetic axis and the axis of rotation would ultimately tend to coincide.
>
> (Page 16:) If we could adopt Dr. SCHMIDT's numbers as final, they would show that the outside magnetic potential is displaced toward the east. Such an effect might be produced by currents induced in a medium rotating more rapidly than the earth, which might be the case if the upper currents of the atmosphere had a general drift from west to east. The displacement of the outside potential, according to Dr. SCHMIDT, is, however, greater than 90°, which is difficult to reconcile with the hypothesis of induced currents under any circumstances.

The following objections must, therefore, be interposed to the idea of accepting BAUER's theory to account for his electric vectors: (1) The conductivity of the ether is far too small, even admitting that anything of the kind exists in its normal state—that is, when under no strain of disruptive electric forces—to give the electric currents required by such induction; for if the conductivity is zero the electric forces vanish. (2) The conductivity of the atmosphere is also much too small to generate the electric vectors by the differential rotation of the atmosphere and the surface of the earth, as already shown by the preceding experiments of ELSTER and GEITEL; also, the atmospheric relative motion is not in one direction, such as the HERTZ induction requires, but it is eastward in the higher latitudes and westward in the tropical regions, except at very high altitudes, and this would necessarily produce a very different distribution of the induced currents from those here required. (3) Dr. A. W. **Rucker** in describing **Bauer's** result says (Nature, December 16, 1897):

> If the immediate surroundings of the earth are electrically conducting, the mere rotation of the huge magnetic mass of the earth itself would cause the production of currents which at some points would flow out of, and at others would flow into the surface.

This ascribes the effect to an electrically conducting ether, but conductivity of the ether is denied by most physicists, though there are some who advocate the possibility of such a property existing to some degree in the ether.

On the other hand, **Trabert** (Meteorol. Zeits., November, 1898) in discussing the subject does not refer to **Bauer's** analogue of the **Hertz** rotating sphere, but tries to show how similar electric currents are probable by the merely *mechanical convection* of charged masses in the several latitudes of the earth; while **Elster** and **Geitel** (Terr. Mag., March, 1899) in reviewing **Trabert's** paper prefer the theory of ionization, which has been explained in the preceding pages, to account for the phenomenon of the induced electric currents, and they do not mention the theory of induction by rotation. (4) The several attempts to verify the **Schmidt** theory of earth-air electric currents by taking line integrals on small regions of the earth where the magnetic surveys have been most minute and accurate have practically failed. Thus, **Rucker** in England, **von Bezold** in Germany, **Carlheim Gyllensköld** in Sweden, and **Liznar** in Austria, have each found the line integrals in all cases well within the limits of the probable errors of the surveys. All these results indicate that (1) there is no conductivity of the ether worth considering as a source of induction of electric currents, and (2) that such as does exist is probably the meteorological effect of solar radiation through ionization and the allied processes.

We can account for our residual vectors, in part at least, by applying the vector formula, $\mathbf{h} = V.\,\mathbf{Dq}$, where $\mathbf{h}$ is the magnetic force produced by the motion $\mathbf{q}$ of the medium containing an electric displacement $\mathbf{D}$, and is directed at right angles to the plane $\mathbf{Dq}$ in the right-hand rotation; this motion is a direct cause for the secondary magnetic vectors of figure 4, Chart 31. Thus the $\mathbf{D}$ lines are positive from the upper strata of the atmosphere towards the earth, which is negative, and the motion $\mathbf{q}$ is eastward in the latitudes from the poles to about ±35°, and westward in the tropical belt. Beginning in the southern or positive hemisphere, we find the first group $\mathbf{h} = V.\,\mathbf{Dq}$ directed northward, the second group southward; in the northern or negative hemisphere the counterpart groups are oppositely directed. This shows that we have a system of magnetic forces acting in the right direction, and if they are not large enough to entirely account for the residuals by themselves, they will yet guide all the other sources of energy otherwise produced towards the same directions, and so tend to sum them up altogether.

FURTHER EVIDENCE OF A CHARACTERISTIC DISTRIBUTION OF ENERGY IN LATITUDE FROM METEOROLOGICAL DATA.

In order to see whether any evidence of a similar meteorological distribution of energy in latitude exists, the following compilations have been made. The values of the vapor tension in latitude, expressed in millimeters, have been collected together from the Report on the Barometry of the United States, from those of the International Polar Expeditions, from numerous reports in the Tropics and in the southern hemisphere, and they are platted on Chart 32, figure 1. For temperature the **Ferrel** formula has been expanded to five terms, and it represents the mean annual temperature distribution in latitude quite closely. The computation is given in Table 28, and the result is platted on figure 2. The magnetic distribution, and by implication the atmospheric electric current distribution, is transferred to figure 3 of Chart 32 from figure 4 of Chart 31. It is seen that these elements all have a secondary minimum in the middle latitudes. In the case of the temperature it is the harmonic term $-20.95 \cos 2\theta$ which is the chief representative of the secondary variation, though the fourth and the fifth terms contribute to it. The distribution of pressure has not been reproduced here because this is so largely an effect of the dynamical forces of the general circulation as to be somewhat too complicated for this special purpose.

CHART 32.

Variation of the vapor tension, temperature, and magnetic deflecting force, in latitude.

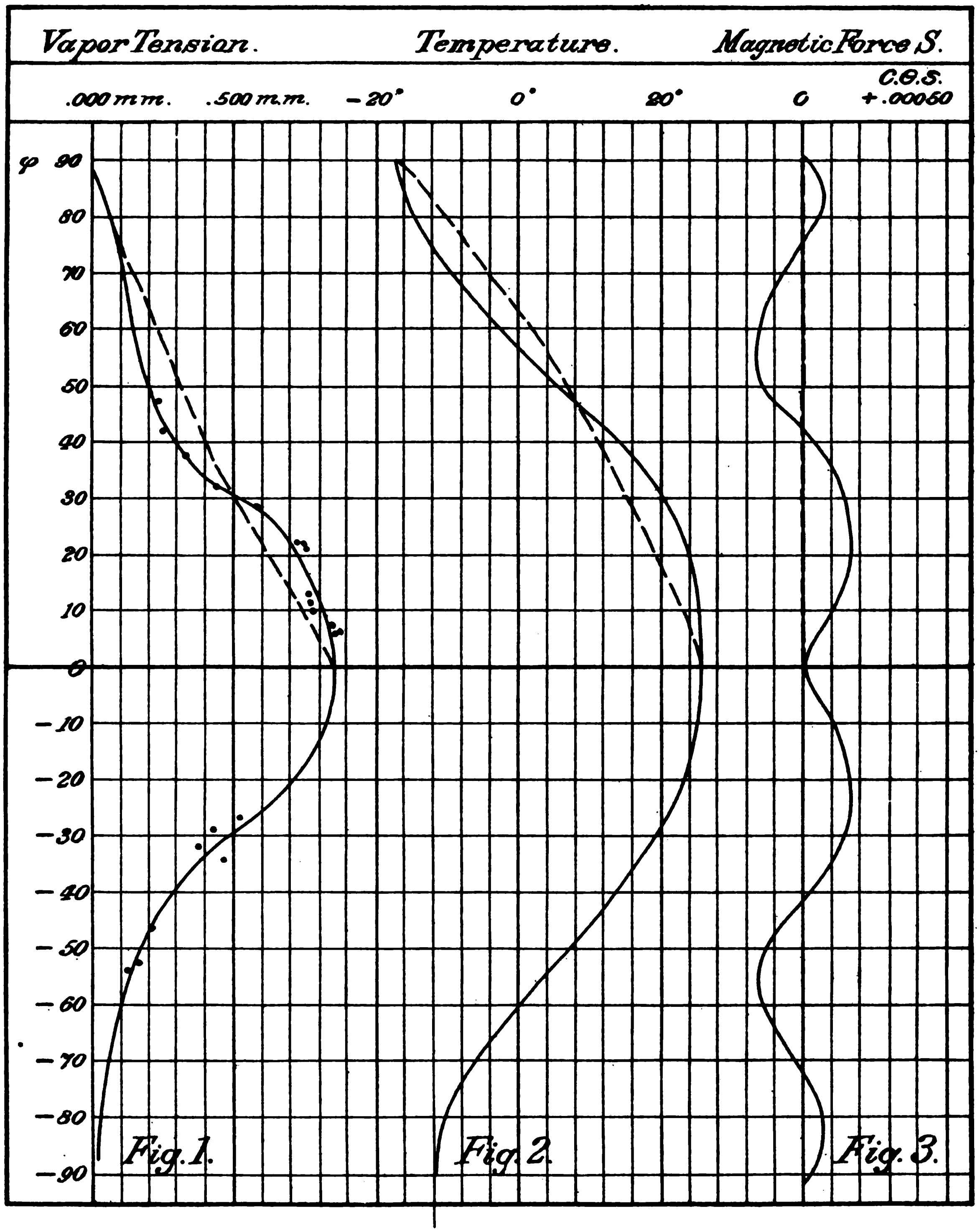

TABLE 28.—*Distribution of temperature in latitude.*

$t = \Sigma A_s \cos s\theta$ = FERREL'S formula. θ = North polar distance.

$A_0 = 8.50$ $A_1 = -1.75$ $A_2 = -20.95$ $A_3 = -1.00$ $A_4 = -2.66$

	cos 0° = 1	cos θ	cos 2θ	cos 3θ	cos 4θ	Sum
θ = 0	1.000	1.000	1.000	1.000	1.000	
10	1.000	.985	.940	.866	.766	
20	1.000	.940	.766	.500	.174	
30	1.000	.866	.500	.000	—.500	
40	1.000	.766	.174	— .500	—.940	
50	1.000	.643	—.174	— .866	—.940	
60	1.000	.500	—.500	—1.000	—.500	
70	1.000	.342	—.766	— .866	.174	
80	1.000	.174	—.940	— .500	.766	
90	1.000	.000	—.100	.000	1.000	
			NORTHERN HEMISPHERE			
θ = 0	8.50	—1.75	—20.95	—1.00	—2.66	—17.86
10	8.50	—1.72	—19.65	—0.87	—2.04	—15.78
20	8.50	—1.64	—16.01	--0.50	—0.46	—10.11
30	8.50	—1.52	—10.45	0.00	+1.33	— 2.14
40	8.50	—1.34	— 3.63	+0.50	+2.50	+ 6.53
50	8.50	—1.13	+ 3.63	+0.87	+2.50	+14.37
60	8.50	—0.88	+10.45	+1.00	+1.33	+20.40
70	8.50	—0.60	+16.01	+0.87	—0.46	+24.32
80	8.50	—0.30	+19.65	+0.50	—2.04	+26.31
90	8.50	0.00	+20.95	0.00	—2.66	+26.79
			SOUTHERN HEMISPHERE			
100						+26.0
110						23.8
120						20.2
130						14.9
140						8.2
150						+ 0.9
160						— 5.8
170						—10.6
180						—12.4

CONCLUSIONS.

In general it is noted that the secondary vector systems do harmonize with the main features of the circulation over the entire globe. At the same time the physical processes of convection and ionization also are similarly distributed into two great systems, so that both are intimately associated together. Taking this survey in latitude together with the survey in longitude as revealed in the diurnal variations, it must be conceded that the meteorological, electric, and magnetic forces are bound up closely together, in such a way that they must be explained by the action of one source of energy working so as to produce these several manifestations in the atmosphere. TRABERT, ELSTER and GEITEL have attempted to trace the connection between the

observed variations in the electric displacement gradient for the several latitudes, showing that the cloud belts in the tropics are favorable for electrical currents from the air to the earth, while the two belts of the temperate zones and the equator belt are favorable for currents from the earth to the air, the latter being positive and the former negative. There is, however, no little difficulty in arriving at quantitative results, owing to the imperfection of the observations of the upper atmosphere of nearly all the quantities concerned. Hence, in place of endeavoring to carry the research further at this time, it is better to postpone it to another occasion for a more critical study of the complex physical problems. The physical processes in the atmosphere, involving the magnetic, electrical, and meteorological elements, are without doubt very complex, so that it is not easy to specify exactly how each system reacts upon the others. As regards the cause of the diurnal deflections of the normal magnetic field the following suggestion is offered: If in a given space under entirely normal conditions, which shall be those represented by the mean values for the day, the radiation of the sun enters, the following course of events may take place. As the result of ionization and drainage from a given space of a relatively large number of the negative ions, it is now occupied by a greater number of isolated positive electric charges than before the event. If in the neighboring spaces similar effects take place, but differing quantitatively, it is evident that a new system of electrical repulsions is set up which acts upon the environment. When such differential effects are extended to the entire atmosphere, in the proportion indicated by the diurnal curves, there is caused practically a bodily displacement of electrical energy extending to the whole atmosphere. We have seen that magnetic force is able to deflect the rays of charged particles; also, the electrostatic force is able to do the same thing; the particles move in paths which are at right angles to the magnetic lines but parallel to the electric lines. It is, therefore, quite probable that the ionization of the atmosphere is the cause of the change in the magnetic field, just as much as it is the cause of the change in the electrostatic field. For by it the number of positively charged ions in a unit volume is changed from the normal number, and, if this volume is traversed by weak magnetic lines, it is to be expected that the disturbance will extend to the magnetic field so as to produce a change in the direction and the intensity of the vector. Should this prove to be the fact, we escape from the difficulties connected with attributing the deflecting magnetic vectors to the meteorological circulation, or to the feeble electric currents possible in a nearly nonconducting medium. This indirect action of the solar electro-magnetic field in producing results quite like those which a purely polar magnetic field in its place would cause, is doubtless a more correct description of that phenomenon than the one mentioned in Bulletin No. 21, though the outcome is quite the same for practical purposes. It seems to be as important to understand the exact action of an increase in the number of the ions upon the magnetic field, as that of a magnetic field in deflecting the course of an ionized ray. This can probably be accomplished by laboratory experiments, if it has not already been done.

In glancing backward over the suggestive series of facts that have been brought together as the result of recent physical researches, it seems to be justifiable to remark: (1) The probability that the sun is a strongly magnetized sphere embracing the earth within its field is decidedly increased by the theory of the solar corona as an appendage of electrically charged minute particles of matter, or ions, which are excluded from the polar zones and are distributed along the magnetic lines of force, especially at times of minimum solar activity; and by the view that the corresponding solar magnetic field at the earth is resolvable into two portions—one strictly solar in origin and the other generated within the earth's atmosphere by ionization and allied physical processes. (2) The problems pertaining to the meteorologist must in consequence of this result include a description of the magnetic field as well as the electric field in the atmospheres of the sun and the earth, together with the processes relating to the variation of pressure, temperature, vapor tension, and the circulation of the air. Especially, efforts should be made to measure the magnetic and the electric potentials in the higher strata of the free air, because upon a definite knowledge of them in that place our elucidation of many problems depends. (3) Since the motions of the air depend ultimately upon the effects of solar radiation, and these upon solar activity, it is plain that a thorough examination of the solar polar magnetic and electromagnetic fields should be prosecuted in the interests of general forecasting.

UNIPOLAR DISSIPATION OF NEGATIVE ELECTRICITY IN POLAR LOW ELEVATIONS AND IN TROPICAL HIGH ELEVATIONS.

In the February (1901) number of the Meteorol. Zeit., J. **Elster** gives an interesting account of his measures of the coefficient of the dissipation of electricity in the free atmosphere at different latitudes from Algiers to Spitzbergen. The apparatus used is that described in Terr. Mag., IV, 213, Dec., 1899; also he used an **Exner** apparatus for measures on the potential gradient, which he found to range between 30 and 100 volts per meter. Generally the rate of dissipation of electricity increases with the clearness of the atmosphere, and decreases with the increased amount of the causes of obscurity, such as dust, fog, mist, etc. The negative electricity dissipates faster than the positive electricity; the rate increases with the altitude above the sea level, because the air is clearer; the wind has no effect upon the rate of dissipation; the rate of dissipation does not depend upon the latitude; the conductivity of the air is less in continental than in ocean climates. All these phenomena are measures of the relative freedom of the air from dust and other causes of opacity.

A peculiar fact was, however, brought out, namely, that the conductivity of the air for negative electricity increases faster than for positive electricity with the latitude, so that in Spitzbergen the negative electricity dissipates two or three times as fast as the positive, whereas in Algiers the rate is about the same. This same fact is also found to prevail at high altitudes in low latitudes, so that we may infer that the phenomenon of increased dissipation of negative electricity begins at the ground in the north polar latitudes, follows a surface which arches high over the tropical latitudes, and descends again near the south polar regions. In this respect the polar regions and the elevated tropical regions are more favorable for the conduction of negative electricity than for positive. We also note that this arching surface outlines the region within which the vapor contents of the atmosphere are for the most part confined, the low polar and the high tropical strata being very dry, on account of the dependence of aqueous vapor upon the temperature of the air, since at low pressures the absolute vapor content is very small. Also it is found from the balloon ascensions in middle latitudes that the region of the phenomenon of active atmospheric electricity is confined to about 5,000 meters, as shown by the disappearance of the potential gradient. In a word, the presence of electricity is largely associated with the vapor contents of the atmosphere. Since ionization by solar radiation seems to be the cause of the electric potential fall, we think it must be derived from the effect of this action specifically upon the aqueous vapor of the atmosphere. The unipolar dissipation, when it goes so far as to be pronounced, is a means of marking the upper boundary of the locus of the activity of the vapor tension; also, the ratio of $\frac{a_-}{a_+}=q$, the rate of dissipation of the negative to the positive electricity, may be used to draw similar curved surfaces or arches through the atmosphere from the polar to the tropical regions, and thus map off the atmosphere according to this property of it. I have introduced this point to emphasize the intimate dependence between the magnetic forces operating in the polar regions, as in the aurora, and the presence of the negative electricity there, for which it has a special affinity. The fact that it is the negative electric discharge in vacuum tubes and cathode radiation generally which is deflected by the magnetic field is in harmony with the idea that these two fields of force interact upon one another in the atmosphere, because an increase in negative electricity must deflect a normal magnetic field just as much as an increase in a magnetic field must deflect a mass of negative ions.

H. **Ebert** has succeeded in measuring the coefficients of dissipation of the positive a_+ and the negative a_- electricity in balloons soaring at considerable heights, with the result that the unipolar character of the electricity seems to disappear in the free air at moderate distances above the ground, since q is nearly equal to unity, i. e., $q=\frac{a_-}{a_+}=1$.

DEFLECTION OF THE EARTH'S MAGNETIC AND ELECTRIC FIELDS BY A CHANGE IN THE AMOUNT OF THE SOLAR RADIATION.

It has been sought by many magnéticians to escape from the difficulties of the theory of the direct magnetic action of the sun upon the earth through a curved or polar field by an appeal to the hidden potentialities of the solar radiation, especially the invisible waves of shorter length than those seen in the visible spectrum. It is evident that in order to account for the multitude of variations observed in the earth's magnetic field there must be equivalent variations in the solar radiation on both sides of the normal. This view will, however, probably break down before the two following facts: (1) That no variations in the solar radiation have been detected corresponding to those in the magnetic field, although the shifting of the solar lines has been carefully studied; and (2) that the large disturbance variations do not come from the same vector field as the diurnal variations, but generally from a vector field lying athwart it. Thus it is found that when a violent disturbance is taking place with a wide deflection of the normal field, the diurnal system of component vectors is transformed hour by hour into that of the polar field which carries the disturbing vectors. This is just opposite to what would be the case if an intensification of the solar radiation is the true cause of the great disturbance vectors, as distinguished from the diurnal vectors. Till these two objections are removed, the hypothesis of a variable action in the radiant field is merely a conjectural view.

We have, however, two distinct examples of the effect of a change in the radiation upon the diurnal components. (1) The change from day to night, when the solar radiation is changed from its maximum to a total withdrawal, is an example of what variation can be made by that source of difference. In no case is it found to produce the system of polar magnetic disturbances, which are directed closely along the magnetic meridians, as stated above in Table 25. A comparison of Chart 30 with Charts 29, 31, and 32 is sufficient comment upon this statement.

We have, moreover, in Dr. L. A. BAUER's observations on the eclipse of May 28, 1900,* a second example of such action. It is shown that during the withdrawal of the sunlight in part or wholly during the passage of the shadow there was a small but distinct variation in the elements of the magnetic field, which must be attributed to that cause. The variations are all feeble, but apparently distinct enough to be of consideration. The time of the duration of the oscillation was about the same as that of the eclipse; the total range of the oscillation was about one minute in arc for the declination and about 0.00008 C. G. S. for the horizontal component; the effect was to deflect the declination needle westward before but eastward after the totality; to decrease the horizontal intensity before and to increase it after the maximum obscuration; the vertical intensity decreased at the time of totality; the cause is apparently outside the earth's surface and it moved along the belt of totality, lagging somewhat behind the moon's shadow; this oscillation is to be referred, probably, to some change produced in the upper regions of the atmosphere by the temporary withdrawal of the sun's rays through the interposition of the moon's body.

Furthermore, J. ELSTER observed in the same eclipse at Mustapha, Algiers, the potential fall in volts during the passage of the shadow, and found that a minimum voltage occurred at the time of the totality. (Terr. Mag., September, 1900, p. 127.) R. LUDEWIG (Beiblätter 23, p. 857, 1899) observed the same fact of a minimum of the electric potential in the eclipse of January 22, 1898.

All these facts taken together show that the solar radiation is able to simultaneously change the magnetic force and the electric force in the atmosphere, and this is in itself a direct confirmation of the view advocated in this report. (Compare also "The magnetic theory of the solar corona," by FRANK H. BIGELOW, Amer. Journ. Sci., April, 1901.) If we refer them to the theory of ionization in the atmosphere, as explained above, we have a chain of physical causes and effects which is so clear and probable that we may expect to find further confirmation of its truth in other directions.

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* Résumé of magnetic observations made chiefly by the United States Coast and Geodetic Survey on the day of the total solar eclipse, May 28, 1900. By L. A. Bauer: Terr. Mag., December, 1900.

Arrhenius proposes the view that the ions generated in the sun are propelled by the pressure of the electromagnetic radiation outward into planetary spaces, and at the planets and comets cause the well-known types of radiation. But it is evident that the comet tail is a radiation beginning at the head itself, and so is caused by the formation of ions in the nucleus of the comet instead of by ions transported from the sun. At the earth the "Gegenschein" is a planetary tail on the side of the astmosphere distant from the sun, and therefore it is an effect of the ions produced in the atmosphere which trail off into space. It seems to me more probable that the sun's radiation produces these ions *in situ* in the gases of the upper strata of the earth's atmosphere than that they are propelled to the earth from the sun, and I have preferred to consider the other attendant phenomena from this point of view rather than from that suggested by Arrhenius.

CHAPTER 5.

FUNDAMENTAL PHYSICAL RELATIONS.

GENERAL REMARKS.

It must be evident from an examination of the contents of Chapter 4 that the higher meteorology of the future will deal vigorously with the fundamental physical relations which are involved in electricity and magnetism, radiation, and the spectrum analysis. It has seemed to me desirable to prepare a brief synopsis of the most important of the mathematical equations for the sake of ready reference by students of these subjects. The works of Oliver Heaviside, J. J. Thomson, and H. Hertz are especially valuable in this connection, and they are, in many respects, fundamental in modern science. Heaviside and Hertz have brought together the duplex relations of electricity and magnetism, while Thomson has made important advances in the physics of matter. Thomson has followed closely in the steps of Maxwell in his method of analysis, while Heaviside has developed a new symbolic system of some obscurity to superficial readers, but in reality of great power and value in the advancement of science. There has been difficulty in securing the attention of students familiar with the Maxwellian system, and persuading them to use Heaviside's notation, but it is clear that the latter work is held in higher favor now than it was some years ago. I have attempted to assist the transition from one system to the other by exhibiting plainly in one common notation the corresponding quantities, especially in the elementary equations. Heaviside uses the terms scalar, vector, vector potential, potential slope, divergence, curl, circuitation, etc., in their defined sense, and operates with them freely through the most complex conditions. It would not be possible to carry the Maxwellian coordinate system through these changes without the utmost complexity and even confusion in the mathematics.

Heaviside differs from other authors chiefly by introducing the use of a system of units which gives *one line* of force from a unit pole instead of 4π *lines*. The common system makes the squared unit of length, as one square centimeter, the unit area, and the force falling upon it from the pole the unit; this would make 4π units pass through the spherical surface surrounding the pole. The difference comes to this, shall we use a plane square area as the unit or the spherical area at the same distance from the pole? The common system is so firmly embedded in our mathematics that it has become very hard to dislodge it, even in a good cause, and I suspect that the two systems must live together as best they may for some time to come. The advantages of the unit system, as used by Heaviside, are very considerable, and I have tried in some respects to bridge the gap between the systems by indicating with a parenthesis (4π) in the fundamental Tables 29 and 30 the place that 4π should have in order to reduce the Heaviside system to the common system. This plan is, however, dropped after the equations in Table 32, from which point the Heaviside system prevails without modification. In Table 34, Symbolic Operations, the symbols $\overset{\text{I}}{\Sigma}$ (line) $\overset{\text{II}}{\Sigma}$ (surface) $\overset{\text{III}}{\Sigma}$ (volume) for summation have been used for the ordinary $\left(\int\cdot\int\int\cdot\int\int\int\cdot\right)$ symbols of integration. It is desirable to study these subjects in the following texts in order to arrive at a working knowledge of these tables:

1. Electromagnetic Theory, by O. **Heaviside.**
2. Electrical Papers, by O. **Heaviside.**
3. Recent Researches in Electricity and Magnetism, by J. J. **Thomson.**
4. Elements of Electricity and Magnetism, by J. J. **Thomson.**
5. Electricity and Magnetism, by **James Clerk Maxwell.**
6. The Mathematical Theory of Electricity and Magnetism, by **Watson** and **Burbury.**
7. The Theory of Electricity and Magnetism, by A. G. **Webster.**
8. Electrical Waves, by H. **Hertz.**
9. Maxwell's Theorie der Electricität und des Lichtes, von L. **Boltzmann.**
10. Physik des Aethers, von **Paul Drude.**
11. Électricité et Optique, par H. **Poincaré.**
12. Magnetische Kraftfelder, von H. **Ebert.**

It may be noted that in the first volume of **Heaviside**'s electrical papers the 4π appears in the equations as it would in the common system, but that it is laid aside generally in the second volume and in the electro-magnetic theory. He seems to have made the transition by experience with his own system, but this fact makes it easy for others to follow the same process of transformation.

CONTENTS OF THE FOLLOWING TABLES.

Tables 29 and 30 give the fundamental relations in electricity and magnetism in the **Heaviside** system, with the (4π) indicated for the common system. The duplex formation of the relations is carefully preserved in the symmetrical arrangement. Table 31 contains J. J. **Thomson**'s electro-magnetic system and notation. In Chart 33 are shown the mutual relations of the fundamental vectors. If the component proper to the axis is taken for each, as (X for E), (β for H), (w for C), then the construction of the following formula can be made without confusion of the primary relations. Table 32 gives the cross connections between electricity and magnetism as embodied in **Heaviside**'s laws of circuitation and the quantities derivable from them. Table 33 exhibits the equations of motion for nearly all possible mechanical relations, and also one of several possible mechanical analogues, though none of them are without objection. Table 34 gives a collection of symbolic operations, Table 35 some inverse operations, and Table 36 the relations between potential, slope, divergence, and curl. Table 37 contains several cases of magnetic fields caused by moving electric charges, and these are very useful in atmospheric discussions. Table 38 contains the notation and the most important equations in the papers by J. J. **Thomson** and J. H. **Jeans** on the conductivity of electricity through gases by charged ions. Table 39 summarizes several papers written on the **Zeeman** effect. Table 40 gives the most important results of the theory of the shifting and broadening of spectrum lines by means of variations of the temperature, density, and pressure of the gases. Table 41 summarizes the radiation function in the spectrum. Table 42 contains the most important formulæ used in computing the heliographic positions of sun spots or other points on the sun.

I have tried to group these formulæ together in such a way that a student once familiar with the original papers may find the notation and the analytic relations in a convenient form for ready reference. The subjects of solar physics, meteorology, electricity and magnetism are so firmly interwoven together, that it has become a necessity to have some such helps in their study, unless their very magnitude is to prevent a broad and comprehensive knowledge of this great department of science. I have had the benefit of Mr. **Heaviside**'s correspondence in preparing the explanatory synopsis of his system.

EXPLANATORY SYNOPSIS OF HEAVISIDE'S SYSTEM.

A dielectric supports two kinds of disturbance, electric and magnetic. The electric force $\mathbf{E}$ produces, or is associated with, the displacement $\mathbf{D}$, and the magnetic force $\mathbf{H}$ produces the displacement $\mathbf{B}$. Thus,

$$\mathbf{D}=c\mathbf{E} \qquad \mathbf{B}=\mu\mathbf{H}$$

In an ideal dielectric c and μ are constants, such that $\mu cv^2=1$, if v is the velocity of propagation of disturbances.

Spacial displacement, or a translation a given distance and in a given direction, is the primitive vector, and all quantities derivable from it by differentiation are also vectors. Thus, velocity and acceleration; then force by a scalar multiplication; or electric force and magnetic force in the same way (e. g., $\mathbf{E}\rho$ is the moving force of $\mathbf{E}$ on ρ of electrification), then electric current and so on. The polygon of displacements is obvious; that of all vectors follows. The *activity* of a force $\mathbf{F}$ with velocity $\mathbf{v}$ is $\mathbf{Fv}$, whether they are parallel or not. When parallel, $\mathbf{Fv}$ is the same as Fv. In general $\mathbf{Fv}=Fv\cos(\widehat{\mathbf{Fv}})$. This defines the scalar product of any two vectors. Similarly the activities of $\mathbf{E}$ and $\mathbf{H}$ are $\mathbf{E\dot{D}}$ and $\mathbf{H\dot{B}}$. The electric and magnetic *energies stored* are:

$$U=\int\mathbf{E\dot{D}}dt=\int_o^D\mathbf{E}d\mathbf{D} \qquad T=\int\mathbf{H\dot{B}}dt=\int_o^B\mathbf{H}d\mathbf{B}$$

When $\mathbf{D}$ and $\mathbf{B}$ are linearly related to $\mathbf{E}$ and $\mathbf{H}$

$$U=\tfrac{1}{2}\mathbf{ED}=\tfrac{1}{2}\mathbf{E}c\mathbf{E} \qquad T=\tfrac{1}{2}\mathbf{HB}=\tfrac{1}{2}\mathbf{H}\mu\mathbf{H}$$

Here c and μ need not be scalar constants, but the linear operators turning $\mathbf{E}$ to $\mathbf{D}$ or $\mathbf{H}$ to $\mathbf{B}$. If they are constants, as in the ether,

$$U=\tfrac{1}{2}cE^2 \qquad T=\tfrac{1}{2}\mu H^2$$

In material bodies these equations may also be approximately true, with changed values of c and μ, caused by matter. In most bodies μ is a trifle greater or a trifle less than in ether, but in some bodies (magnetic) largely greater. Then the linear relation is not true for small forces. $\mathbf{B}$ does not depend on $\mathbf{H}$ alone on account of hysteresis. On the other hand, c is always increased little or much, but not enormously, like μ in iron. The linear relation also loses full validity. It is in crystalline media that c and μ become linear operators. Then $\mathbf{D}=c\mathbf{E}$ means $D_1=c_1E_1$, $D_2=c_2E_2$, $D_3=c_3E_3$, if $D_1D_2D_3$, are the components of D and $E_1E_2E_3$, those of E in the three mutually $\perp$ directions, in which D or E are parallel, whilst $c_1c_2c_3$ are the principal permittivities. Similarly with μ. If μ_o, c_o are the etherial constants, then $\frac{\mu}{\mu_o}$, $\frac{c}{c_o}$ are the specific inductivity and specific permittivity, mere numerics, like specific gravity, equal to the ratio of weight or mass of one body to that of a standard body of the same bulk.

Besides storing energy, bodies can not support electric force without wasting energy. In an electric dielectric

$$Q_1=\mathbf{EC}=\mathbf{E}k\mathbf{E} \quad \text{(rate of waste)}$$

$$\mathbf{C}=\ k\mathbf{E} \quad \text{(Ohm's Law, for the unit volume).}$$

If k is the conductivity, $\mathbf{C}$ the conduction current, k may be a linear operator, but if only a scalar constant, so that $\mathbf{E}\parallel\mathbf{C}$ (parallel to), then $Q_1=EC=kE^2$.

The reciprocal of k is the resistivity. The total activity of $\mathbf{E}$ is now

$$\mathbf{E}(\mathbf{C}+\mathbf{\dot{D}})=Q_1+\dot{U}$$

Similarly, in a magnetic conductor (if it existed) we should have

$$\mathbf{H}(\mathbf{G}+\mathbf{\dot{B}})=Q_2+\dot{T},$$

where $\mathbf{G}$ is the magnetic conduction current, and $Q_2=\mathbf{HG}$, $\mathbf{G}=g\mathbf{H}$, so that g is the magnetic conductivity (fictitious).

$\mathbf{C}+\dot{\mathbf{D}}$ is the true electric current in MAXWELL's sense, and $\mathbf{G}+\dot{\mathbf{B}}$ would be the true magnetic current. But in reality it is only $\dot{\mathbf{B}}$. These true currents have to be supplemented later.

The line integral of the effective electric force along any path is the *voltage* or E. M. F.; the line integral of the magnetic force along any path is the *gaussage* or M. M. F.

Everything relating to $\mathbf{E}$ and $\mathbf{H}$ concerns the unit cube, its volume, side, edge. When we pass to voltage and gaussage we require to consider the total fluxes through areas, and total wastes in volumes, in their relation to voltage and gaussage. Thus,

$$\begin{array}{lll} \mathbf{C}=k\mathbf{E} & \text{becomes } C=KV & \text{or } V=RC \\ \mathbf{D}=c\mathbf{E} & \text{becomes } Q=SV & \\ \mathbf{B}=\mu\mathbf{H} & \text{becomes } P=LC & \end{array}$$

It is convenient to distinguish between the *density* of a *flux* and the *intensity* of a *force*.

K is the conductance (electric) of a wire, for example.
R is the resistance (electric) of a wire, for example.
S is the permittance of a condenser.
S^{-1} is the elastance of a condenser.
L is the inductance of a magnetic circuit or portion thereof.
L^{-1} is the reluctance of a magnetic circuit or portion thereof.
Q is the charge of the condenser.
P is the momentum of the current C, line integral of effective $\mathbf{H}$ embracing C.

The energy of condenser is $\frac{1}{2}SV^2=\frac{1}{2}VQ$.

The energy of current is $\frac{1}{2}LC^2=\frac{1}{2}CP$.

The activity of the voltage is, when condenser is also conducting:

$$V(C+\dot{Q})=RC^2+\frac{d}{dt}(\tfrac{1}{2}SV^2)$$

In the core of the coils it is convenient as regards the external connections to make the current in any turn be C instead of the total current in all.

Thus, $P=(L_1N)C$ is the flux of induction through any turn; L_1 signifies now the permeance and the energy is $\frac{1}{2}P(NC)=\frac{1}{2}(L_1N^2)C^2=\frac{1}{2}LC^2$. This L is the inductance. If there is only one turn of wire, then it and the permeance are the same. It is N^2 times the permeance of the turns.

CROSS CONNECTIONS OF ELECTRIC AND MAGNETIC PHENOMENA.

First circuital law.—The positive circuitation of the magnetic force measures the electric current.

Second circuital law.—The negative circuitation of the electric force measures the magnetic current.

These apply to any circuit (closed line) irrespective of material. The circuitation is once along and around the circuit. The current is the total through the closed line. Thus, the circuital gaussage measures the electric current, and the negative of the circuital voltage measures the magnetic current.

Passing to unit volume the fluxes are $\mathbf{J}$ $\mathbf{G}$ (true currents).

$$\left.\begin{array}{ll} \text{The first circuital law is} & \operatorname{curl} \mathbf{H}_1=\mathbf{J} \\ \text{" second " " "} & -\operatorname{curl} \mathbf{E}_1=\mathbf{G} \end{array}\right\} \text{in a stationary medium, unelectrified.}$$

Take unit area $\perp$ to $\mathbf{J}$ and $\mathbf{G}$ in order to identify with the more general forms above of the circuital laws. Curl is therefore the circuitation per unit area $\perp$ to the flux.

$\mathbf{H}_1$ and $\mathbf{E}_1$ are the forces of the field, not counting impressed or intrinsic forces.

Equation of activity $\mathbf{EJ}+\mathbf{HG}=Q+\dot{U}+\dot{T}$ when there are no impressed forces.

Total in all space $\quad 0=\Sigma(Q+\dot{U}+\dot{T})=Q_0+\dot{U}_0+\dot{T}_0$.

If the impressed forces are $\mathbf{f}$ and the velocities are $\mathbf{v}$ then

$$\Sigma \mathbf{fv} = Q_o + \dot{U}_o + \dot{T}_o.$$

If impressed forces are of electricity and magnetism, type $\mathbf{e}$ and $\mathbf{h}$, then

$$\Sigma\ (\mathbf{eJ} + \mathbf{hG}) = Q_o + \dot{U}_o + \dot{T}_o$$

only true in total since fluxes of energy are not considered.

If $\mathbf{H}$ and $\mathbf{E}$ are forces of the fluxes $\mathbf{D}$ and $\mathbf{B}$ and if also intrinsic or impressed forces $\mathbf{h}$ and $\mathbf{e}$ exist, then

$$\mathbf{H} = \mathbf{H}_1 + \mathbf{h} \qquad \mathbf{E} = \mathbf{E}_1 + \mathbf{e}$$

It is $\mathbf{H}_1$ and $\mathbf{E}_1$ that occur in circuital laws or

$$\text{curl } (\mathbf{H} - \mathbf{h}) = \mathbf{J}.$$

$$-\text{curl } (\mathbf{E} - \mathbf{e}) = \mathbf{G}.$$

$\mathbf{e}$ may include voltaic force, thermoelectric force, force of intrinsic electrification, impressed electric force, etc.

$\mathbf{h}$ may include force of intrinsic magnetization, impressed magnetic force, etc.

Intrinsic electrification is the function of displacement, temporary or permanent, $\mathbf{I}_1 = c\mathbf{e}$:

Intrinsic magnetization is the function of induction, temporary or permanent, $\mathbf{I}_2 = \mu\mathbf{h}$.

The mechanical product $V\mathbf{ab}$ of $\mathbf{a}$ and $\mathbf{b}$ is a vector of the size $\mathbf{ab} \sin \mathbf{a}{}^\wedge\mathbf{b} \perp$ to both $\mathbf{a}$ and $\mathbf{b}$, with the right-handed screw relation between +translation and +rotation.

Thus, if $\mathbf{a}$ is to the north and $\mathbf{b}$ to the east, then $V\mathbf{ab}$ is downward; $V\mathbf{ab} = -V\mathbf{ba}$.

The mechanical electric force is $\mathbf{e} = V\mathbf{qB}$, the mechanical magnetic force is $\mathbf{h} = V\mathbf{Dq}$, when $\mathbf{q}$ is the velocity of the medium. It is a quasi-impressed force introduced to let the circuital laws be true for a moving medium.

Thus $$\begin{array}{rl} \text{curl } (\mathbf{H} - V\mathbf{Dq}) = \mathbf{J} & \left\{ \begin{array}{l} \text{unelectrified moving medium and} \\ \text{no intrinsic forces.} \end{array} \right\} \\ -\text{curl } (\mathbf{E} - V\mathbf{qB}) = \mathbf{G} & \end{array}$$

Express the same circuital laws when the medium is moving; $\mathbf{q}$ the velocity at any point.

Electromagnetic force is $V\mathbf{JB}$. (Moving force, unit volume.)
Magnetoelectric force is $V\mathbf{DG}$.
Their activities are $\mathbf{q}\,V\mathbf{JB}$ and $\mathbf{q}\,V\mathbf{DG}$
or $\mathbf{J}\,V\mathbf{Bq}$ and $\mathbf{G}\,V\mathbf{qD}$
or $-\mathbf{eJ}$ and $-\mathbf{hG}$

Looking from the other side, the negatives of $V\mathbf{JB}$ and $V\mathbf{DG}$ are the impressed mechanical forces; so $\mathbf{e} = V\mathbf{qB}$ and $\mathbf{h} = V\mathbf{Dq}$ are the equivalent impressed electric and magnetic forces.

General.—The divergence of any flux is the amount leaving the unit volume.

Special.—The divergence of the displacement is the density of the electrification.

Electrification $\rho = \text{div } D$
Magnetification $\sigma = \text{div } B$ (fictitious)

or electrification is the source of displacement, when not circuital,

$$D = \frac{\rho}{4\pi r^2} \qquad B = \frac{\sigma}{4\pi r^2}$$

are the densities of D and B at distance r, due to ρ or σ, when spreading isotropically from the point.

When electrification moves it makes an electric current. The true currents, then, are

$$\mathbf{J}=\mathbf{C}+\dot{\mathbf{D}}+\rho\mathbf{u}$$

$$\mathbf{G}=\mathbf{K}+\dot{\mathbf{B}}+\sigma\mathbf{w}$$

when there is ρ and σ moving at the place. Use these in the circuital laws, omitting, however the q terms if medium is at rest. **quw** may be all different, at least.

HEAVISIDE'S VECTORIAL ANALYSIS.

Scalars are in roman type, P (x . y . z.)
Vectors are in black letters, **D** . **e**.

Scalar product, $\mathbf{ab}=ab\cos\widehat{\mathbf{ab}}$.

Vector product, $V\mathbf{ab}=ab\sin\widehat{\mathbf{ab}}$, and ⊥ to **a** and **b**.
The tensor or size of a vector **A** is A; components A_1, A_2, A_3

Vector differentiator, $\nabla=\mathrm{i}\frac{d}{dx}+\mathrm{j}\frac{d}{dy}+\mathbf{k}\frac{d}{dz}$; $\nabla_1=\frac{d}{dx}$; $\nabla_2=\frac{d}{dy}$; $\nabla_3=\frac{d}{dz}$.

The *slope* of a scalar P in its space variation:

$$\nabla P=\mathrm{i}\frac{dP}{dx}+\mathrm{j}\frac{dP}{dy}+\mathbf{k}\frac{dP}{dz}=\text{a vector.}$$

Usually $-\triangle$ the slope downwards is considered.
The *divergence* of a vector **D** is the scalar product:

$$\nabla\mathbf{D}=\operatorname{div}\mathbf{D}=\frac{dD_1}{dx}+\frac{dD_2}{dy}+\frac{dD_3}{dz}.$$

The *curl* of a vector **E** is the vector product:

$$V\nabla\mathbf{E}=\mathrm{i}\left(\frac{dE_3}{dy}-\frac{dE_2}{dz}\right)+\mathrm{j}\left(\frac{dE_1}{dz}-\frac{dE_3}{dx}\right)+\mathbf{k}\left(\frac{dE_2}{dx}-\frac{dE_1}{dy}\right).$$

Physical examples.

Scalars.—Density, pressure, temperature, potential, etc.

Vectors.—Displacement, velocity, force, electric current, etc.

The divergence of any flux **D** is the strength of D.

The curl of magnetic force is electric current.

Any physical magnitude is a vector that can be derived from the fundamental vector spacial distribution by differentiation—e. g., velocity and acceleration; then force by multiplying by a scalar; then electric and magnetic force in the same way; then electric current, etc.

The polygon of displacements is obvious, and the same follows for all vectors.

Common system: 4π lines of force emanate from the unit pole.

Heaviside's system: One line of force emanates from the unit pole.

TABLE 29.—*Electricity.*

FUNDAMENTAL RELATIONS.

(Omit the factor (4π) in order to transpose from common to Heaviside's units.)

1.	c	*Permittivity.* or Spec. Ind. Capac.	$\frac{1}{(4\pi)}c\mathbf{E}=\mathbf{D}$	S	*Permittance.*	$Q=SV$ Charge.
2.	$\frac{1}{c}$	Elastivity.	$\frac{1}{c}(4\pi)\mathbf{D}=\mathbf{E}$	$\frac{1}{S}$	Elastance.	$V=\frac{Q}{S}$
3.	k	*Conductivity.*	$\mathbf{C}=k\mathbf{E}$	K	*Conductance.*	$C=KV$
4.	$\frac{1}{k}$	Resistivity.	$\frac{1}{k}\mathbf{C}=\mathbf{E}$	R	Resistance.	$V=RC=\frac{1}{K}C$
5.	$\frac{c}{c_o}$	Specific permittivity or dielectric constant.		P	Momentum.	$P=LC$
6.	ρ	Electrification or volume density=charge				$\rho=\mathrm{div}\ \mathbf{D}$; Also $\rho=\frac{R}{2L}+\frac{K}{2S}$
7.	$\mathbf{e}_o$	Intrinsic electric force (voltaic, thermoelectric)				$\mathbf{e}_o=\frac{1}{c}\mathbf{I}_1$
8.	$\mathbf{e}$	Motional electric force.				$\mathbf{e}=V\mathbf{qB}$
9.	$\mathbf{E}$	Electric force of flux	$\mathbf{E}\ (\mathbf{X}\ .\ \mathbf{Y}\ .\ \mathbf{Z})$			$\mathbf{E}=\mathbf{E}_1+\mathbf{e}$
10.	$\mathbf{E}_1$	Electric force of field.				$\mathbf{E}_1=(\mathbf{E}-\mathbf{e}_o-\mathbf{e})$
11.	$\mathbf{D}$	Displacement	$\mathbf{D}\ (\mathbf{f}\ .\ \mathbf{g}\ .\ \mathbf{h})$			$\mathbf{D}=\frac{c\mathbf{E}}{(4\pi)}=SV=Q$ for a condenser.
12.	(V)	Line integral of electric force=voltage.				$(V)=\frac{1}{S}D$
13.	$\mathbf{C}$	Conduction current	$\mathbf{C}\ (\mathbf{u}\ .\ \mathbf{v}\ .\ \mathbf{w})$			$\mathbf{C}=k\mathbf{E}.$
14.	$\mathbf{D}$	Displacement current	$\dot{\mathbf{D}}\left(\frac{\partial f}{\partial t}\cdot\frac{\partial g}{\partial t}\cdot\frac{\partial h}{\partial t}\right)$			
15.	$\rho\mathbf{u}$	Convection current	$\rho\ (\dot{x}\ .\ \dot{y}\ .\ \dot{z})$			
16.	$\mathbf{j}$	Electric current due to motion of medium.				$(4\pi)\mathbf{j}=\mathrm{curl}\ \mathbf{h}=\mathrm{curl}\ V\mathbf{Dq}$
17.	Γ_1	Maxwell's electric current	$\Gamma_1(\mathbf{p}\ .\ \mathbf{q}\ .\ \mathbf{r})$			$\Gamma_1=\mathbf{C}+\dot{\mathbf{D}}=k\mathbf{E}+\frac{c\dot{\mathbf{E}}}{(4\pi)}=\mathrm{curl}\ \mathbf{H}\frac{1}{(4\pi)}$
18.	$\mathbf{J}$	True electric current.				$\mathbf{J}=\mathbf{C}+\dot{\mathbf{D}}+\rho\mathbf{u}=\mathrm{curl}\ \mathbf{H}_1\frac{1}{(4\pi)}$
19.	$\mathbf{J}_o$	Total electric current in moving medium.				$\mathbf{J}_o=\mathbf{C}+\dot{D}+\rho\mathbf{u}+\mathbf{j}$
20.	Q_1	Joulean waste, as in a wire.				$Q_1=k\mathbf{E}^2=\mathbf{CE}.$
21.	U	Electric energy stored.	$U=\int_o^D\mathbf{E}d\mathbf{D}$ generally;			$U=\frac{1}{2}\mathbf{ED}=\frac{1}{2}\frac{c\mathbf{E}^2}{(4\pi)}$
22.	P	Potential.				
23.	$\mathbf{F}$	Mechanical force.	$\mathbf{fq}=$work.			$\mathbf{F}=V\mathbf{CB}$
24.	$\mathbf{I}_1$	Intrinsic electrization.				$\mathbf{I}_1=c\mathbf{e}\frac{1}{(4\pi)}$
25.	$\mathbf{W}$	Flux of energy.				$(4\pi)\mathbf{W}=V(\mathbf{E}-\mathbf{e}_o)(\mathbf{H}-\mathbf{h}_o)=V\mathbf{E}_1\mathbf{H}$
26.	ψ	Current function.				
27.	Ψ	Potential of free electricity.				
28.	φ	Velocity potential.				
29.	A	Vector potential.	$\mathbf{A}\ (\mathbf{F}.\ \mathbf{G}.\ \mathbf{H}.)$			$\mathbf{A}=\mathbf{EJ}+\mathbf{HG}=Q+\dot{U}+\dot{T}$

TABLE 30.—*Magnetism.*

FUNDAMENTAL RELATIONS.

(Omit the factor (4π) in order to transpose from common to Heaviside's units.)

30.	μ	*Inductivity.*	$\mathbf{B}=\mu\mathbf{H}=[1+(4\pi)\kappa]\,\mathbf{H}$		L	*Inductance*	$P=LC$
					L_1	Permeance	$P=(L_1N)C$
31.	κ	Susceptibility.	$\mathbf{I}=\kappa\mathbf{H}$		$\frac{1}{L}$	Reluctance	$C=\frac{1}{L}P$
32.	g	Magnetic conductivity.	$\mathbf{K}=g\mathbf{H}$		(R)	Magnetic conductance	$K=(R)G$
33.	$\frac{1}{g}$	Magnetic resistivity.	$\frac{1}{g}\mathbf{K}=\mathbf{H}$		K	Leakage conductance.	
34.	$\frac{\mu}{\mu_o}$	Specific inductivity or permeability.	$\frac{\mu}{\mu_o}=1+(4\pi)\kappa$				
35.	σ	Magnetification. (nonexistent)		$\sigma=\text{div }\mathbf{B}$		Also $\sigma=\frac{R}{2L}-\frac{K}{2S}$	
36.	$\mathbf{h}_o$	Intrinsic magnetic force (intrinsic magnetization of magnets).		$\mathbf{h}_o=\frac{1}{\mu}\mathbf{I}_2$			
37.	$\mathbf{h}$	Motional magnetic force as induced.		$\mathbf{h}=V\mathbf{Dq}\times(4\pi)$			
38.	$\mathbf{H}$	Magnetic force of flux	$\mathbf{H}\ (\alpha\ .\ \beta\ .\ \gamma)$	$\mathbf{H}=\mathbf{h}+\mathbf{H}_1$			
39.	$\mathbf{H}_1$	Magnetic force of field.		$\mathbf{H}_1=\mathbf{H}-\mathbf{h}_o-\mathbf{h}$			
40.	$\mathbf{B}$	Magnetic induction	$\mathbf{B}\ (\mathbf{a}\ .\ \mathbf{b}\ .\ \mathbf{c})$	$\mathbf{B}=\mu\mathbf{H}$			
41.	(G)	Line integral of magnetic force=Gaussage.		$\mathbf{G}=-\text{curl }\mathbf{E}_1$			
42.	$[\mathbf{K}]$	Magnetic conduction current (fictitious).		$[\mathbf{K}]=g\mathbf{H}$			
43.	$\sigma\mathbf{w}$	Convection current.	$\sigma\ (\dot{x}\ .\ \dot{y}\ .\ \dot{z})$				
44.	$\mathbf{g}$	Magnetic current due to motion.		$\mathbf{g}=-\text{curl }\mathbf{e}\,\frac{1}{(4\pi)}$			
45.	Γ_2	(Maxwell's) magnetic current.		$\Gamma_2=[\mathbf{K}]+\frac{1}{(4\pi)}\dot{\mathbf{B}}=-\frac{\text{curl }\mathbf{E}}{(4\pi)}$			
46.	$\mathbf{G}$	True magnetic current.		$\mathbf{G}=[\mathbf{K}]+\frac{1}{(4\pi)}\dot{\mathbf{B}}+[\sigma\mathbf{w}]=-\frac{\text{curl }\mathbf{E}_1}{(4\pi)}$			
47.	$\mathbf{G}_o$	Total magnetic current in moving medium.		$\mathbf{G}_o=[\mathbf{K}]+\frac{1}{(4\pi)}\dot{\mathbf{B}}+[\sigma\mathbf{w}]+\mathbf{g}$			
48.	Q_2	Joulean waste (fictitious).		$Q_2=g\mathbf{H}^2=\mathbf{KH}$			
49.	T	Magnetic energy stored.	$T=\int_o^{\mathbf{B}}\mathbf{H}\,\frac{d\mathbf{B}}{(4\pi)}$ generally;	$T=\frac{1}{2}\,\frac{\mathbf{HB}}{(4\pi)}=\frac{1}{2}\,\frac{\mu\mathbf{H}^2}{(4\pi)}$			
50.	$\mathbf{A}$	Vector potential or momentum	$\mathbf{A}\ (\mathbf{F}\ .\ \mathbf{G}\ .\ \mathbf{H})$	$\mathbf{A}=\mathbf{EJ}+\mathbf{HG}=Q+\Gamma'+\dot{T}$			
51.	$\mathbf{I}_2$	Intrinsic magnetization	$\mathbf{I}_2\ (\mathbf{A}\ .\ \mathbf{B}\ .\ \mathbf{C})$	$\mathbf{I}_2=-\nabla\Omega=\mu\mathbf{h}\,\frac{1}{(4\pi)}=\kappa\mathbf{F}$			
52.	Ω	Magnetic potential.					

TABLE 31.—*J. J. Thomson's electromagnetic system and notation.*

[Recent Researches; Phil. Mag., July, 1889; Elements.]

(In common units.)

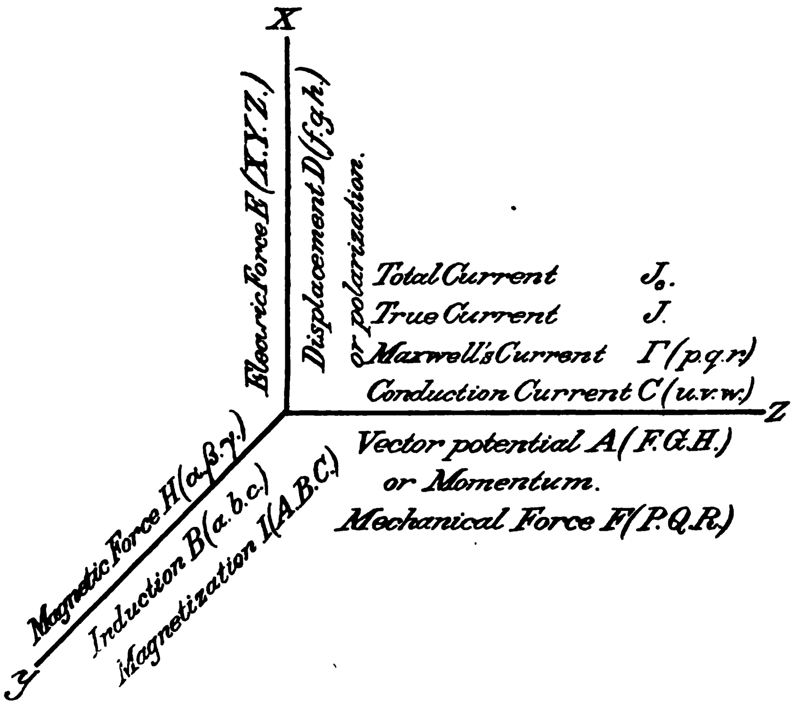

CHART 33.—Relative axial relations of the electric and magnetic quantities.

f_x= the number of electrostatic lines at the point xyz through the unit area at right angles to x; f_y to y; f_z to z.

This may be changed in three ways:

1. By bringing new lines into the area.
2. By spreading or contracting the lines through their relative motion.
3. By changing the direction of the lines through rotation.

These give the strength, divergence, and rotation of the field.

53. 1. $\delta_1 f_x = -\delta t\left(u\frac{\partial f}{\partial x}+v\frac{\partial f}{\partial y}+w\frac{\partial f}{\partial z}\right)$. Number of new lines added.

2. $\delta_2 f_x = -\delta t f\left(\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)$. Number added through convergence.

3. $\delta_3 f_x = \delta t\left(g\frac{\partial u}{\partial y}+h\frac{\partial u}{\partial z}\right)$. Number added by deflection of direction.

54. Total variation. $\delta f_x=\delta_1 f+\delta_2 f+\delta_3 f=\left[-\left(u\frac{\partial f}{\partial x}+v\frac{\partial f}{\partial y}+w\frac{\partial f}{\partial z}\right)-f\left(\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}\right)+\left(g\frac{\partial u}{\partial y}+h\frac{\partial u}{\partial z}\right)\right]\delta t.$

55. $\frac{df_x}{dt}=\frac{\partial}{\partial y}(ug-vf)-\frac{\partial}{\partial z}(wf-uh)-u\left(\frac{\partial f}{\partial x}+\frac{\partial g}{\partial y}+\frac{\partial h}{\partial z}\right)$.

56. Density. ρ=density of free electricity$=\frac{\partial f}{\partial x}+\frac{\partial g}{\partial y}+\frac{\partial h}{\partial z}$.

57. Maxwell's current.

$$\Gamma_1=\begin{cases} p=\dfrac{\partial f}{\partial t}+u\rho=\dfrac{\partial}{\partial y}(ug-vf)-\dfrac{\partial}{\partial z}(wf-uh). \\ q=\dfrac{\partial g}{\partial t}+v\rho=\dfrac{\partial}{\partial z}(vh-wg)-\dfrac{\partial}{\partial x}(ug-vf). \\ r=\dfrac{\partial h}{\partial t}+w\rho=\dfrac{\partial}{\partial x}(wf-uh)-\dfrac{\partial}{\partial y}(vh-wg). \end{cases}$$

Rate of variation of the electric field through displacement and convection currents.

58. First circuital law.

$$4\pi J=\begin{cases} 4\pi p=\dfrac{\partial \gamma}{\partial y}-\dfrac{\partial \beta}{\partial z}. \\ 4\pi q=\dfrac{\partial \alpha}{\partial z}-\dfrac{\partial \gamma}{\partial x}. \\ 4\pi r=\dfrac{\partial \beta}{\partial x}-\dfrac{\partial \alpha}{\partial y}. \end{cases}$$

The positive magnetic circuitation measures the electric current through the circuit.

59. Second circuital law.

$$4\pi G=\begin{cases} -\dfrac{\partial a}{\partial t}=\dfrac{\partial Z}{\partial y}-\dfrac{\partial Y}{\partial z}. \\ -\dfrac{\partial b}{\partial t}=\dfrac{\partial X}{\partial z}-\dfrac{\partial Z}{\partial x}. \\ -\dfrac{\partial c}{\partial t}=\dfrac{\partial Y}{\partial x}-\dfrac{\partial X}{\partial y}. \end{cases}$$

The negative electric circuitation measures the magnetic current through the circuit.

The motion of an electrostatic line gives rise to a magnetic force at right angles to itself and to the direction of motion. $h=VDq$.

60. Magnetic force.

$$H=\begin{cases} \alpha=4\pi(vh-wg). \\ \beta=4\pi(wf-uh). \\ \gamma=4\pi(ug-uf). \end{cases}$$

The vector product is referred to the right-handed rotation and translation for the axes $x\,.\,y\,.\,z$.

Let c=the specific inductive capacity for electricity in the medium.
μ=the specific inductive capacity for magnetism in the medium.
k=the coefficient of conductivity in matter for electricity.
κ=the coefficient of induced magnetization. $\mu=1+4\pi\kappa$.

Electric force is due to the motion of electrostatic lines in a medium whose specific inductive capacities are $c\ \mu$.

61. Electric induction or electromotive force.

$$E=\begin{cases} X=\dfrac{4\pi}{c}f=\mu(w\beta-v\gamma)=wb-vc=\dfrac{dT}{df}. \\ Y=\dfrac{4\pi}{c}g=\mu(u\gamma-w\alpha)=uc-wa=\dfrac{dT}{dg}. \\ Z=\dfrac{4\pi}{c}h=\mu(v\alpha-u\beta)=va-ub=\dfrac{dT}{dh}. \end{cases}$$

62. Magnetic induction.

$$B=\begin{cases} a=\mu\alpha=(1+4\pi\kappa)\alpha=\alpha+4\pi A. \\ b=\mu\beta=(1+4\pi\kappa)\beta=\beta+4\pi B. \\ c=\mu\gamma=(1+4\pi\kappa)\gamma=\gamma+4\pi C. \end{cases}$$

63.

$$B=\begin{cases} a=4\pi\mu(vh-wg)=\dfrac{\partial H}{\partial y}-\dfrac{\partial G}{\partial z}. \\ b=4\pi\mu(wf-uh)=\dfrac{\partial F}{\partial z}-\dfrac{\partial H}{\partial x}. \\ c=4\pi\mu(ug-vf)=\dfrac{\partial G}{\partial x}-\dfrac{\partial F}{\partial y}. \end{cases}$$

64. Magnetization. $$I=\begin{cases} A=\kappa\alpha=4\pi\kappa(vh-wg). \\ B=\kappa\beta=4\pi\kappa(wf-uh). \\ C=\kappa\gamma=4\pi\kappa(ug-vf). \end{cases}$$

65. Velocity of transmission. $v^2=\dot{x}^2+\dot{y}^2+\dot{z}^2=\frac{1}{\mu c}$ $\quad \mu c v^2=1.$

The motion of the electrostatic lines involves kinetic energy T.

66. Kinetic energy. $$T=\frac{\mu}{8\pi}(\alpha^2+\beta^2+\gamma^2).$$ $$=2\pi\mu\left[(hu-gw)^2+(fw-hu)^2+(gu-fv)^2\right].$$

67. Momentum per unit volume or vector potential. $$A=\begin{cases} F=\frac{dT}{du}=4\pi\mu\left[g(gu-fv)-h(fw-hu)\right]=gc-hb. \\ G=\frac{dT}{dv}=4\pi\mu\left[h(hv-gw)-f(gu-fv)\right]=ha-fc. \\ H=\frac{dT}{dw}=4\pi\mu\left[f(fw-hu)-g(hv-gw\right]=fb-ga. \end{cases}$$

Direction cosines of the inwardly directed normal to the surface dS.

68. Number of lines of electrostatic force. $$J=\begin{cases} p=c\Sigma g-b\Sigma h=\iint\Sigma f(lu+mv+nw). \\ q=a\Sigma h-c\Sigma f=\iint\Sigma g(lu+mv+nw). \\ r=b\Sigma f-a\Sigma g=\iint\Sigma h(lu+mv+nw). \end{cases}$$

69. Mechanical force. $$F=\begin{cases} P=cq-br. \\ Q=ar-cp. \\ R=bp-aq. \end{cases}$$ This is the force tending to move a conductor which carries a current in a magnetic field.

70. Let ψ=current function=distribution of density over a surface.
Ψ=potential of free electricity.

71. Electrical potential. $P=\iint\frac{\psi}{r}dS.$ P_o=external field; P=outside, P'=inside the surface.

72. Magnetic potential. $\Omega=\iint\frac{d}{dr}\cdot\frac{\psi}{r}dS.$ $\quad \doteq-\frac{1}{a}\frac{d}{dr}(Pr)$ on a sphere.

73. Vector potential. $F=n\frac{dP}{dy}-m\frac{dP}{dz}.$ $\quad G=l\frac{dP}{dz}-n\frac{dP}{dx}.$ $\quad H=m\frac{dP}{dx}-l\frac{dP}{dy}.$

74. Magnetic induction. $\mu\alpha=\frac{dH}{dy}-\frac{dG}{dz}=-\frac{d\Omega}{dx}.$ $\quad \mu\beta=\frac{dF}{dz}-\frac{dH}{dx}=-\frac{d\Omega}{dy}.$ $\quad \mu\gamma=\frac{dG}{dx}-\frac{dF}{dy}=-\frac{d\Omega}{dz}.$

75. Electric force. $X=-\frac{dF}{dt}-\frac{d\Psi}{dx}=\frac{1}{k}u.$ $\quad Y=-\frac{dG}{dt}-\frac{d\Psi}{dy}=\frac{1}{k}u.$ $\quad Z=-\frac{dH}{dt}-\frac{d\Psi}{dz}=\frac{1}{k}w.$

76. Conduction current. $u=n\frac{d\psi}{dy}-m\frac{d\psi}{dz}.$ $\quad v=l\frac{d\psi}{dz}-n\frac{d\psi}{dx}.$ $\quad w=m\frac{d\psi}{dx}-l\frac{d\psi}{dy}.$

77. Maxwell's electric current. $\begin{cases} p_1=k\frac{4\pi}{c}f=kX=u. \\ p_2=\frac{df}{dt}. \end{cases}$ $\quad \begin{cases} q_1=k\frac{4\pi}{c}g=kY=v. \\ q_2=\frac{dg}{dt}. \end{cases}$ $\quad \begin{cases} r_1=k\frac{4\pi}{c}h=kZ=w. \\ r_2=\frac{dh}{dt}. \end{cases}$

TABLE 32.—*Connections between electricity and magnetism.*

[In Heaviside's units.]

CIRCUITATION.

78. I. First circuital law: The *positive* magnetic circuitation measures the electric current through the circuit.

79. II. Second circuital law: The *negative* electric circuitation measures the magnetic current through the circuit.

80. I. $\text{curl}\,\mathbf{H}_1 = \text{curl}\,(\mathbf{H}-\mathbf{h}_o-\mathbf{h}) = (4\pi)\,\mathbf{J} = (4\pi)\left(\mathbf{C}+\frac{1}{(4\pi)}\dot{\mathbf{D}}+\rho\mathbf{u}\right).$

or $\text{curl}\,(\mathbf{H}-\mathbf{h}_o) = (4\pi)\,\mathbf{J}_o = (4\pi)\left(\mathbf{C}+\frac{1}{(4\pi)}\dot{\mathbf{D}}+\rho\mathbf{u}+\mathbf{j}\right).$

81. II. $-\text{curl}\,\mathbf{E}_1 = -\text{curl}\,(\mathbf{E}-\mathbf{e}_o-\mathbf{e}) = (4\pi)\mathbf{G} = (4\pi)\left(\mathbf{K}+\frac{1}{(4\pi)}\dot{\mathbf{B}}+\sigma\mathbf{w}\right).$

or $-\text{curl}\,(\mathbf{E}-\mathbf{e}_o) = (4\pi)\mathbf{G}_o = (4\pi)\left(\mathbf{K}+\frac{1}{(4\pi)}\dot{\mathbf{B}}+\sigma\mathbf{w}+\mathbf{g}\right).$

82. Electric energy of medium. $U=\frac{1}{2}\mathbf{ED}=\frac{1}{2}\frac{c\mathbf{E}^2}{(4\pi)}=\frac{1}{2}\frac{\mathbf{E}c\mathbf{E}}{(4\pi)}$ $\quad \frac{1}{2}DV=\frac{1}{2}SV^2$. Condenser.

83. Magnetic energy of medium. $T=\frac{1}{2}\frac{\mathbf{HB}}{(4\pi)}=\frac{1}{2}\frac{\mu\mathbf{H}^2}{(4\pi)}=\frac{\mathbf{H}\mu\mathbf{H}}{(4\pi)}$ $\quad \frac{1}{2}PC=\frac{1}{2}LC^2$. Current in a circuit.

84. Activity. $Q_1+\dot{U}=\mathbf{EC}+\mathbf{E}\dot{\mathbf{D}}$ $\quad Q_2+\dot{T}=\mathbf{HK}+\mathbf{H}\dot{\mathbf{B}}.$

$\Sigma(Q_1+Q_2+\dot{U}+\dot{T})=\Sigma(\mathbf{EJ}+\mathbf{HG})=\Sigma[\mathbf{fq}+\text{conv}\,(\mathbf{A}+\mathbf{q}\,(U+T))].$

85. Flux of energy. Stress flux. $\mathbf{A}=-\left[V\mathbf{eH}+V\mathbf{Eh}+\mathbf{q}(U+T)\right].$

86. Poynting flux. $\mathbf{W}=V(\mathbf{E}-\mathbf{e}_o)(\mathbf{H}-\mathbf{h}_o)\frac{1}{(4\pi)}.$

$\mathbf{W}=V\mathbf{EH}\,\frac{1}{(4\pi)}$ when there are no intrinsic forces.

$\mathbf{W}=\mathbf{q}(U+T)$ in plane waves and solar radiation.

87. Convective flux. $\mathbf{F}_q=Q_o+U_o+T_o+\text{div}\,q(U_o+T_o).$

88. Medium at rest. $\mathbf{e}_o\mathbf{J}+\mathbf{h}_o\mathbf{G}=Q+\dot{U}+\dot{T}+\text{div}\,\mathbf{W}.$

89. Medium in motion. $\mathbf{e}_o\mathbf{J}_o+\mathbf{h}_o\mathbf{G}_o=Q+\dot{U}+\dot{T}+\mathbf{Fq}+Sa+\text{div}\left[\mathbf{W}+\mathbf{A}+\mathbf{q}(U+T)\right].$

90. Mechanical moving forces. Electric. $\mathbf{F}_e=\mathbf{E}\rho-\frac{1}{2}\mathbf{E}^2\nabla c+[V\mathbf{DG}_o]+V\mathbf{Dg}_o.$

91. Magnetic. $\mathbf{F}_m=[\mathbf{H}\sigma]-\frac{1}{2}\mathbf{H}^2\nabla\mu+V\mathbf{J}_o\mathbf{B}+V\mathbf{j}_o\mathbf{B}.$

92. Complete. $\mathbf{F}=V\dot{\mathbf{D}}\mathbf{B}+V\mathbf{D}\dot{\mathbf{B}}=\frac{d}{dt}V\mathbf{DB}=\frac{1}{v^2}\frac{d\mathbf{W}}{dt}.$ Uncharged condenser.

93. Radiation. $v=$Velocity. $\mathbf{E}=\mu v\mathbf{H}.$ $\quad V=Lv\mathbf{C}.$ $\quad LSv^2=1.$

$\mathbf{H}=cv\mathbf{E}.$ $\quad C=SvV.$ $\quad \mu cv^2=1.$

94. For distortionless transmission. $\frac{R}{L}=\frac{K}{S}$ or $\frac{g}{\mu}=\frac{k}{c}.$

95. Attenuation factor. For total displacement. $\varepsilon^{-\frac{Kt}{S}}$ or $\varepsilon^{-\frac{Kt}{C}}.$

96. For total induction. $\varepsilon^{-\frac{Rt}{L}}$ or $\varepsilon^{-\frac{gt}{\mu}}.$

97. For head of wave. $\varepsilon^{-\frac{Kt}{2C}}$ or $\varepsilon^{-\frac{Kt}{2S}}$ or $\varepsilon^{-\frac{gt}{2\mu}}$ or $\varepsilon^{-\frac{Rt}{2L}}.$

TABLE 33.—*Equations of motion. Mechanical analogue.*

[In Heaviside's units.]

Coefficients of	Elasticity	Friction	Inertia	Analogue	Notation
98. Translation	$\rho=\rho_o$	$+\ \rho_1\frac{d}{dt}$	$+\ \rho_2\frac{d^2}{dt^2}$	. . . . . mass	Thomson and Tait's notation.
99. Compression	$k=k_o$	$+\ k_1\frac{d}{dt}$	$+\ k_2\frac{d^2}{dt^2}$	Solidity (solid)	$m=k+\frac{1}{3}n$.
100. Distortion	$n=n_o$	$+\ n_1\frac{d}{dt}$	$+\ n_2\frac{d^2}{dt^2}$	Rigidity (jelly)	$n+m=k+\frac{4}{3}n$.
101. Rotation	$\nu=\nu_o$	$+\ \nu_1\frac{d}{dt}$	$+\ \nu_2\frac{d^2}{dt^2}$	. . . . . (ether)	

102. Translation. $\mathbf{f}+\mathbf{F}=\left(\rho_o+\rho_1\frac{d}{dt}+\rho_2\frac{d^2}{dt_2}\right)\mathbf{G}$ $\mathbf{G}$=spacial displacement.

103. Strain. $\mathbf{N}\nabla\mathbf{G}=\mathbf{p}_n-\frac{1}{2}V\mathbf{N}\text{ curl }\mathbf{G}=(\mathbf{p}_n-\frac{1}{3}\mathbf{N}\text{ div }\mathbf{G})+\frac{1}{3}\mathbf{N}\text{ div }\mathbf{G}-\frac{1}{2}V\mathbf{N}\text{ curl }\mathbf{G}$.

104. Equation of motion. $\rho\ddot{\mathbf{G}}=\mathbf{f}+n\nabla^2\mathbf{G}+m\nabla\text{ div }\mathbf{G}$ in ordinary elastic solid.

105. Circuital stress. $\rho\mathbf{G}_1=\mathbf{f}_1+n\nabla^2\mathbf{G}_1$. speed$=\left(\frac{n}{\rho}\right)^{\frac{1}{2}}$.

106. Divergent stress. $\rho\ddot{\mathbf{G}}_2=\mathbf{f}_2+(n+m)\nabla^2\mathbf{G}_2$. speed$=\left(\frac{n+m}{\rho}\right)^{\frac{1}{2}}$.

107. Equilibrium. $\mathbf{f}_1=-n\nabla^2\mathbf{G}_1$. $\mathbf{f}_2=-(n+m)\nabla^2\mathbf{G}_2$.

108. Solid (elastic). $\mathbf{f}_1=\left(\rho\frac{d^2}{dt^2}-n\nabla^2\right)\mathbf{G}$. viscous $\mathbf{f}_1=\left[\rho\frac{d^2}{dt^2}-\left(n_o+n_1\frac{d}{dt}\right)\nabla^2\right]\mathbf{G}$.

109. Liquid. viscous $\mathbf{f}_1=\left[\rho\frac{d^2}{dt^2}-n_1\frac{d}{dt}\nabla^2\right]$

$\mathbf{G}=\rho\frac{d\mathbf{q}}{dt}-n_1\nabla^2\mathbf{q}$.

110. Ether (rotational). $\mathbf{f}_1=\left(\rho\frac{d^2}{dt^2}-\nu\nabla^2\right)\mathbf{G}=\left(\rho\frac{d}{dt}-\nu\int\nabla^2\right)\mathbf{q}=\rho\frac{d}{dt}\mathbf{q}+$ curl $(\frac{1}{2}\mathbf{S})$.

	Distortion	Compression	Rotation
111. Strain.	$\mathbf{N}\nabla\mathbf{G}=(\mathbf{p}_n-\frac{1}{3}\mathbf{N}\text{ div }\mathbf{G})$	$+\frac{1}{3}\mathbf{N}\text{ div }\mathbf{G}$	$-\frac{1}{2}V\mathbf{N}\text{ curl }\mathbf{G}$.
112. Stress.	$\mathbf{P}_n=2n(\mathbf{p}_n-\frac{1}{3}\mathbf{N}\text{ div }\mathbf{G})$	$+\mathbf{N}k\text{ div }\mathbf{G}$	$-\nu V\mathbf{N}\text{ curl }\mathbf{G}$.
113. Torque.	$\mathbf{S}=$		$2\nu\text{ curl }\mathbf{G}$.
114. Translational force.	$\mathbf{F}=n(\nabla^2\mathbf{G}+\frac{1}{3}\nabla\text{ div }\mathbf{G})$	$+k\nabla\text{div }\mathbf{G}$	$-\nu\text{ curl}^2\mathbf{G}$.
115. Energy of strain.	$\mathbf{U}=n\left[(\mathbf{p}_1^2+\mathbf{p}_2^2+\mathbf{p}_3^2-\frac{1}{3}(\text{div }\mathbf{G})^2)\right]$	$+\frac{1}{2}k(\text{div }\mathbf{G})^2$	$+\frac{1}{2}\nu(\text{curl }\mathbf{G})^2$.

116. Appropriate mechanical analogue of the *rotational ether;* with $E=q=\frac{dG}{dt}$.

$$\begin{array}{lllll}
\mathbf{G}=f\mathbf{E} & \rho=c & \mathbf{f}_1=\tfrac{1}{2}\,\mathrm{curl}\;\mathbf{S}_o & \rho\mathbf{q}=\mathbf{D} & \rho_1\mathbf{q}=\mathbf{C}=k\mathbf{E}. \\
\mathbf{q}=\mathbf{E} & \frac{1}{\nu}=\mu & \mathbf{g}_1=-\mathrm{curl}\;\mathbf{q}_o & \tfrac{1}{2}\rho\mathbf{q}^2=\tfrac{1}{2}c\mathbf{E}^2 & \tfrac{1}{2}\rho_o\mathbf{q}^2=\tfrac{1}{2}\mu\mathbf{H}^2. \\
\quad =\text{a velocity} & & & & \\
 & \rho_1=k & -\tfrac{1}{2}\mathbf{S}_o=\mathbf{h} & \rho_1\mathbf{q}^2=k\mathbf{E}^2 & V\tfrac{1}{2}\mathbf{S}\mathbf{q}=V\mathbf{E}\mathbf{H}. \\
 & \left(\rho_1+\rho\frac{d}{dt}\right)\mathbf{q}=\mathbf{C}+\dot{\mathbf{D}} & -\tfrac{1}{2}\mathbf{S}=\nu\;\mathrm{curl}\;\mathbf{G}=\mathbf{H} & & -\frac{1}{\nu}\tfrac{1}{2}\;\mathbf{S}=\mathbf{B}=-\mathrm{curl}\;\mathbf{G}.
\end{array}$$

$\mathbf{N}$ is the normal component in all cases.
$\mathbf{f}$ is the impressed force per unit volume.
$\mathbf{p}_n$ is the stress on the plane whose normal is $\mathbf{N}$.
$\mathbf{F}$ is the force arising from stress.
ρ is the density.
$\mathbf{G}$ is the spacial displacement.

TABLE 34.—*Symbolic operations.*

[In Heaviside's units.]

CIRCUITAL TO SURFACE SUMMATIONS (CURL).

From boundary to surface.

117. P=scalar; $\mathbf{H}$=vector; $\mathbf{T}$=unit tangent to curve; $\mathbf{N}$=unit normal to surface.
f=symbol for function.
$\overset{|}{\Sigma}$=line summation or integral around a curve.
$\overset{||}{\Sigma}$=surface summation or integration.
$\overset{|||}{\Sigma}$=volume summation or integration.

118. $\overset{|}{\Sigma}f(\mathbf{T})=\overset{||}{\Sigma}f(VN\nabla)$.

119. Curl theorems:

$$\left\{\begin{array}{llll}
a. & f(\mathbf{T})=\mathbf{T}. & \overset{|}{\Sigma}\mathbf{T} & =0 \quad \text{Closed polygon or any circuit of vectors.} \\
b. & f(\mathbf{T})=\mathbf{T}P. & \overset{|}{\Sigma}\mathbf{T}P & =\overset{||}{\Sigma}\,V\mathbf{N}\nabla.P \qquad =\overset{||}{\Sigma}\,V\mathbf{N}(\nabla P)=\overset{||}{\Sigma}\mathbf{N}\;\mathrm{curl}\;\mathbf{H}. \\
c. & f(\mathbf{T})=\mathbf{T}\mathbf{H}. & \overset{|}{\Sigma}\mathbf{T}\mathbf{H} & =\overset{||}{\Sigma}(V\mathbf{N}\nabla)\mathbf{H} \qquad =\overset{||}{\Sigma}\mathbf{N}\,V\nabla\mathbf{H} \quad =\overset{||}{\Sigma}\mathbf{N}\;\mathrm{curl}\;\mathbf{H}. \\
d. & f(\mathbf{T})=V\mathbf{T}\mathbf{H}. & \overset{|}{\Sigma}\,V\mathbf{T}\mathbf{H} & =\overset{||}{\Sigma}\,V(V\mathbf{N}\nabla)\mathbf{H} \qquad =\overset{||}{\Sigma}(\nabla\mathbf{H}\mathbf{N}-\mathbf{N}\nabla\mathbf{H}). \\
e. & f(\mathbf{T})=(V\mathbf{T}\mathbf{N})P. & \overset{|}{\Sigma}\,V\mathbf{T}\mathbf{N}P & =\overset{||}{\Sigma}\,V(V\mathbf{N}\nabla)\mathbf{N}\,.\,P=\overset{||}{\Sigma}(\nabla P-\mathbf{N}\,.\,\mathbf{N}\nabla P).
\end{array}\right.$$

SURFACE TO VOLUME SUMMATIONS (DIVERGENCE).

From closed surface to inclosed region.

120. P=scalar; $\mathbf{D}$=vector; $\mathbf{N}$=normal from surface; p=a constant or variable.

121. $\overset{||}{\Sigma}f(\mathbf{N})=\overset{|||}{\Sigma}f(\mathbf{D})$.

122. Divergence theorems:

a. $f(\mathbf{N})=\mathbf{N}.$ $\overset{\prime\prime}{\Sigma}\mathbf{N}=0$ Balanced volume.

b. $f(\mathbf{N})=\mathbf{N}p.$ $\overset{\prime\prime}{\Sigma}\mathbf{N}p=0$ p constant.

$$=\overset{\prime\prime\prime}{\Sigma}\nabla p=\overset{\prime\prime\prime}{\Sigma}\left(\frac{d.ip}{dx}+\frac{d.jp}{dy}+\frac{d.kp}{dz}\right)p \text{ variable.}$$

c. $f(\mathbf{N})=\mathbf{ND}.$ $\overset{\prime\prime}{\Sigma}\mathbf{ND}=\overset{\prime\prime\prime}{\Sigma}\operatorname{div}D=\overset{\prime\prime\prime}{\Sigma}\left(\frac{dD_1}{dx}+\frac{dD_2}{dy}+\frac{dD_3}{dz}\right).$

d. $f(\mathbf{N})=\mathbf{ND}P.$ $\overset{\prime\prime}{\Sigma}\mathbf{ND}P=\overset{\prime\prime\prime}{\Sigma}\nabla(\mathbf{D}P)=\overset{\prime\prime\prime}{\Sigma}\nabla\mathbf{D}P+\overset{\prime\prime\prime}{\Sigma}\mathbf{D}\nabla P.$

$$=\overset{\prime\prime\prime}{\Sigma}P\left(\frac{dD_1}{dx}+\frac{dD_2}{dy}+\frac{dD_3}{dz}\right)+\overset{\prime\prime\prime}{\Sigma}\left(D_1\frac{dP}{dx}+D_2\frac{dP}{dy}+D_3\frac{dP}{dz}\right).$$

e. $f(\mathbf{N})=V\mathbf{NH}.$ $\overset{\prime\prime}{\Sigma}V\mathbf{NH}=\overset{\prime\prime\prime}{\Sigma}\left(\frac{d.ViH}{dx}+\frac{d.VjH}{dy}+\frac{d.VkH}{dz}\right).$

$$=\overset{\prime\prime\prime}{\Sigma}V\nabla H.$$

$$=\overset{\prime\prime\prime}{\Sigma}\operatorname{curl}H.$$

$$=\overset{\prime\prime\prime}{\Sigma}\left[i\left(\frac{dH_3}{dy}-\frac{dH_2}{dz}\right)+j\left(\frac{dH_1}{dz}-\frac{dH_3}{dx}\right)+k\left(\frac{dH_2}{dx}-\frac{dH_1}{dy}\right)\right].$$

TABLE 35.—*Inverse operations.*

[In Heaviside's system.]

123. Inverse to divergence. $p.\ q.$ scalar:

$\nabla(pq)=p\nabla q+q\nabla p.$ $\overset{\prime\prime}{\Sigma}\mathbf{N}pq=\overset{\prime\prime\prime}{\Sigma}\nabla(pq)$ $\therefore\ \overset{\prime\prime\prime}{\Sigma}p\nabla q+\overset{\prime\prime\prime}{\Sigma}q\nabla p=0.$

124. Inverse to slope. p scalar, $\mathbf{g}$ vector:

$\operatorname{div}(p\mathbf{g})=p\operatorname{div}\mathbf{g}+\mathbf{g}\nabla p.$ $\overset{\prime\prime}{\Sigma}\mathbf{N}p\mathbf{g}=\overset{\prime\prime\prime}{\Sigma}\operatorname{div}(p\mathbf{g})\ \therefore\ \overset{\prime\prime\prime}{\Sigma}p\operatorname{div}\mathbf{g}=-\overset{\prime\prime\prime}{\Sigma}\mathbf{g}\nabla p.$

125. Inverse to curl:

$\operatorname{curl}(p\mathbf{g})=p\operatorname{curl}\mathbf{g}-V\mathbf{g}\nabla p.$ $\overset{\prime}{\Sigma}\operatorname{curl}(p\mathbf{g})=\overset{\prime\prime\prime}{\Sigma}V\mathbf{N}p\mathbf{g}$ $\therefore\ \overset{\prime\prime}{\Sigma}p\operatorname{curl}\mathbf{g}=\Sigma V\mathbf{g}\nabla_{\lambda}$

Integration by parts.

126. $\overset{\prime\prime\prime}{\Sigma}p\nabla\mathbf{q}=-\overset{\prime\prime\prime}{\Sigma}\mathbf{q}\nabla p.$ $\overset{\prime\prime\prime}{\Sigma}p\operatorname{div}\mathbf{g}=-\overset{\prime\prime\prime}{\Sigma}\mathbf{g}\nabla p.$ $\overset{\prime}{\Sigma}p\operatorname{curl}\mathbf{g}=\overset{\prime\prime}{\Sigma}V\mathbf{g}\nabla p.$

127. $\overset{\prime\prime\prime}{\Sigma}\mathbf{f}\operatorname{curl}\mathbf{g}=\overset{\prime\prime\prime}{\Sigma}\mathbf{g}\operatorname{curl}\mathbf{f}.$ $\overset{\prime\prime\prime}{\Sigma}\mathbf{g}\operatorname{div}\mathbf{f}=-\overset{\prime\prime\prime}{\Sigma}\mathbf{f}\nabla\mathbf{g}.$

Differentiating effects of ∇.

128. Case *a.* $\mathbf{N}V\nabla\mathbf{E}=\nabla V\mathbf{EN}=\mathbf{E}V\mathbf{N}\nabla=(V\mathbf{N}\nabla)\mathbf{E}.$

b. $\nabla V\mathbf{EH}=\mathbf{E}V\mathbf{H}\nabla=\mathbf{H}V\nabla\mathbf{E}\ \therefore\ \operatorname{div}V\mathbf{EH}=\mathbf{H}\operatorname{curl}\mathbf{E}-\mathbf{E}\operatorname{curl}\mathbf{H}.$

c. $\operatorname{curl}V\mathbf{qB}=V\nabla V\mathbf{qB}=\mathbf{q}\nabla\mathbf{B}-\mathbf{B}\nabla\mathbf{q}=\mathbf{q}\operatorname{div}\mathbf{B}+\mathbf{B}\nabla\mathbf{q}-\mathbf{B}\operatorname{div}\mathbf{q}-\mathbf{q}\nabla\mathbf{B}.$

d. $-\operatorname{curl}(\mathbf{E}-\mathbf{e}_o)=\mathbf{K}+\dot{\mathbf{B}}+\mathbf{w}\sigma-\operatorname{curl}V\mathbf{qB}=\mathbf{K}+\frac{d\mathbf{B}}{dt}+\mathbf{B}\operatorname{div}\mathbf{q}-\mathbf{B}\nabla\mathbf{q}+(\mathbf{w}-\mathbf{q})\sigma.$

$\operatorname{curl}(\mathbf{H}-\mathbf{h}_o)=\mathbf{C}+\dot{\mathbf{D}}+\mathbf{u}\rho-\operatorname{curl}V\mathbf{qD}=\mathbf{C}+\frac{d\mathbf{D}}{dt}+\mathbf{D}\operatorname{div}\mathbf{q}-\mathbf{D}\nabla\mathbf{q}+(\mathbf{u}-\mathbf{q})\rho.$

e. $\operatorname{curl}\mathbf{D}P=V\nabla\mathbf{D}P=V\nabla\mathbf{D}P-V\mathbf{D}\nabla P=P\operatorname{curl}\mathbf{D}-V\mathbf{D}\nabla P.$

f. $\operatorname{div.}\operatorname{curl}\mathbf{H}=\nabla V\nabla\mathbf{H}=0.$

g. $\operatorname{curl}\nabla P=(V\nabla\nabla)P=0.$

h. $(\operatorname{curl})^2\mathbf{A}=V\nabla V\nabla\mathbf{A}=\nabla\ .\ \nabla\mathbf{A}-\nabla^2\mathbf{A}=\nabla\operatorname{div}\mathbf{A}-\nabla^2\mathbf{A}.$

$\nabla^2\mathbf{A}=\nabla\operatorname{div}\mathbf{A}-\operatorname{curl}^2\mathbf{A}.$

i. $\nabla^2P=\operatorname{div}\nabla P.$

TABLE 36.—*Relations between.*

In Heaviside's Units.

	Potential	Slope	Divergence	Curl
129.	pot	$-\nabla$	div	$V\nabla$

Definition , $\text{pot}\ x = \Sigma \frac{x}{4\pi r}$ where x is scalar or vector.

130. pot curl = curl pot. $\quad \text{curl}^2\ \text{pot} = 1 \quad \text{div} = -\nabla \quad \text{pot} = -\frac{1}{\nabla^2}$

pot div = div pot. $\quad -\text{pot}\ \nabla\ \text{div} = 1 \quad \text{curl}^2 = -\nabla^2$ on a circuital vector.

These occur with a vector operand. $\quad \nabla\ \text{div} = \nabla^2$ on a noncircuital vector.

$\text{div}\ \nabla = \nabla^2$ on a scalar.

Example , $\rho = \text{div}\ \mathbf{F} = -\nabla^2 P = -\nabla^2 \text{pot}\rho$.

131. *Circuital.*

$$\mathbf{A}_1 = \text{pot}\ \mathbf{C}_1 = \Sigma \frac{\mathbf{C}_1}{4\pi r} = \Sigma \frac{V(\mathbf{B}_1 \mathbf{r}_1)}{4\pi r^2}$$

$$\mathbf{B}_1 = \text{curl}\ \mathbf{A}_1 = \text{curl pot}\ \mathbf{C}_1 = \text{pot}\ \mathbf{D}_1 = \Sigma \frac{V(\mathbf{C}_1 \mathbf{r}_1)}{4\pi r^2}$$

$$\mathbf{C}_1 = \text{curl}^2\ \mathbf{A}_1 = -\nabla^2 \mathbf{A}_1 = \text{curl}^2\ \text{pot}\ \mathbf{C}_1 = \Sigma \frac{V(\mathbf{D}_1 \mathbf{r}_1)}{4\pi r^2}$$

132. *Divergent.*

$$\mathbf{A}_2 = \mathbf{P} = \Sigma \frac{\rho}{4\pi r}. \quad = \frac{\mathbf{B}_2 . \mathbf{r}_1}{4\pi r^2}.$$

$$\mathbf{B}_2 = \mathbf{R} = -\nabla \mathbf{P} = \text{pot}\ \mathbf{D}_2 = \Sigma \frac{\mathbf{C}_2 . \mathbf{r}_1}{4\pi r^2}.$$

$$\mathbf{C}_2 = \text{div}\ \mathbf{R} = 4\pi\rho = -\nabla^2 \mathbf{A}_2.$$

$$= -\nabla\ \text{div}\ \mathbf{A}_2 = \Sigma \frac{\mathbf{D}_2 . \mathbf{r}_1}{4\pi r^2}.$$

$\mathbf{r}_1$ = the unit vector drawn from ρ to the point where r ends.

Any vector with the suffix 1 is circuital and is the curl of the one before it. It is the potential of the second one after it.

$$\mathbf{B}_1 = \text{curl}\ \mathbf{A}_1 = \text{pot}\ \mathbf{D}_1 = \text{curl pot}\ \mathbf{C}_1 = \text{pot curl}\ \mathbf{C}_1.$$

Any vector with the suffix 2 is the divergent slope of the preceding scalar; any scalar is the divergence of the preceding vector; and whether vector or scalar it is the potential of the one after the next.

$$\mathbf{C}_2 = -\nabla \mathbf{B}_2. \quad \mathbf{B}_2 = \text{div}\ \mathbf{A}_2. \quad \mathbf{A}_2 = \text{pot}\ \mathbf{C}_2. \quad \mathbf{B}_2 = \text{pot}\ \mathbf{D}_2.$$

133. **A** $\begin{cases} \mathbf{A}_1 = \text{curl}^2\ \text{pot}\ \mathbf{A}_1 = \text{curl pot}\ \mathbf{B}_1 = \text{pot}\ \mathbf{C}_1. \\ \mathbf{A}_2 = -\text{pot}\ \nabla\ \text{div}\ \mathbf{A}_2 = -\nabla\ \text{pot}\ \mathbf{B}_2 = \text{pot}\ \mathbf{C}_2. \end{cases}$

134. **B** $\begin{cases} \mathbf{B}_1 = \text{curl}\ \mathrm{A}_1 = \text{curl}^2\ \text{pot}\ \mathbf{B}_1 = \text{curl pot}\ \mathbf{C}_1 = \text{pot}\ \mathbf{D}_1. \\ \mathbf{B}_2 = -\nabla \mathbf{A}_2 = -\text{pot div}\ \mathbf{B}_2 = -\nabla\ \text{pot}\ \mathbf{C}_2 = \text{pot}\ \mathbf{D}_2. \end{cases}$

135. **C** $\begin{cases} \mathbf{C}_1 = \text{curl}^2\ \mathbf{A}_1 = \text{curl}\ \mathbf{B}_1 = \text{curl}^2\ \text{pot}\ \mathbf{C}_1 = \text{curl pot}\ \mathbf{D}_1 = \text{pot}\ \mathbf{E}_1. \\ \mathbf{C}_2 = -\nabla^2 \mathbf{A}_2 = -\nabla \mathbf{B}_2 = -\text{pot}\ \nabla\ \text{div}\ \mathbf{C}_2 = -\nabla\ \text{pot}\ \mathbf{D}_2 = \text{pot}\ \mathbf{E}_2. \end{cases}$

136. **D** $\begin{cases} \mathbf{D}_1 = \text{curl}^3\ \mathbf{A}_1 = \text{curl}^2\ \mathbf{B}_1 = \text{curl}\ \mathbf{C}_1 = \text{curl}^2\ \text{pot}\ \mathbf{D}_1 = \text{curl pot}\ \mathbf{D}_1. \\ \mathbf{D}_2 = -\nabla^3 \mathbf{A}_2 = \nabla^2\ \text{div}\ \mathbf{B}_2 = -\nabla \mathbf{C}_2 = -\text{pot}\ \nabla\ \text{div}\ \mathbf{D}_2 = -\nabla\ \text{pot}\ \mathbf{D}_2. \end{cases}$

137. $\begin{cases} \mathbf{A}_1 = \text{curl}^{-1}\ \mathbf{B}_1 = \Sigma \frac{V(\mathbf{B}_1 \mathbf{r}_1)}{4\pi r^2}. \\ \mathbf{A}_2 = \text{div}^{-1}\ \mathbf{B}_2 = \Sigma \frac{\mathbf{B}_2 \mathbf{r}_1}{4\pi r_2}. \end{cases}$

138. $\begin{cases} \mathbf{B}_1 = \text{curl}^{-1}\ \mathbf{C}_1 = \Sigma \frac{V(\mathbf{C}_1 \mathbf{r}_1)}{4\pi r^2}. \\ \mathbf{B}_2 = -\text{div}^{-1}\ \mathbf{C}_2 = \Sigma \frac{\mathbf{C}_2 \mathbf{r}_1}{4\pi r^3}. \end{cases}$

139. $\begin{cases} \mathbf{C}_1 = \text{curl}^{-1}\ \mathbf{D}_1 = \Sigma \frac{(V \mathbf{D}_1 \mathbf{r}_1)}{4\pi r^2}. \\ \mathbf{C}_2 = \text{div}^{-1}\ \mathbf{D}_2 = \Sigma \frac{\mathbf{D}_2 \mathbf{r}_1}{4\pi r^2}. \end{cases}$

$(\mathbf{A}_1.\mathbf{B}_1.\mathbf{r}_1)$, $(\mathbf{B}_1.\mathbf{C}_1\mathbf{r}_1)$, $(\mathbf{C}_1\mathbf{D}_1\mathbf{r}_1)$ are vector systems mutually at right angles to each other.

Vector Potential relations.

(In common units.)

		Electrical.	*Magnetical.*
140.	Displacements.	$\mathbf{D}=\frac{c\mathbf{E}}{4\pi}$	$\mathbf{B}=\mu\mathbf{H}.$
141.	Vector Potentials.	$-\mathbf{Z}=-c\Sigma\frac{\mathbf{G}}{r}=\Sigma\frac{\text{curl } c\mathbf{E}}{4\pi r}$	$\mathbf{A}=\mu\Sigma\frac{\mathbf{\Gamma}}{r}=\Sigma\frac{\text{curl } \mu\mathbf{H}}{4\pi r}.$
142.	Curls.	$-\text{curl } \mathbf{Z}=4\pi\mathbf{D} \quad =c\mathbf{E}$ $-\text{curl } \mathbf{E}=\mu\dot{\mathbf{H}} \quad =4\pi\mathbf{G}$ $\text{curl } c^{-1} \text{ curl } \mathbf{Z}=4\pi\mathbf{G}$	$\text{curl } \mathbf{A}=\mathbf{B} \quad =\mu\mathbf{H}.$ $\text{curl } \mathbf{H}=c\dot{\mathbf{E}} \quad =4\pi\mathbf{\Gamma}.$ $\text{curl } \mu^{-1} \text{ curl } \mathbf{A}=4\pi\mathbf{\Gamma}.$
143.	Energy.	$U=\Sigma\frac{1}{2}\mathbf{ED} =\Sigma\frac{1}{2}\mathbf{ZG}$	$T=\Sigma\frac{1}{2}\frac{\mathbf{HB}}{4\pi}=\Sigma\frac{1}{2}\mathbf{A\Gamma}.$
144.		$-\mathbf{Z}=\mathbf{H}+\nabla\Omega$	$-\mathbf{A}=\mathbf{E}+\nabla P.$

145. If **Z** and **A** are wholly circuital, and

$$\text{div } \mu\dot{\mathbf{Z}}=-4\pi\rho \qquad \text{div } c\dot{\mathbf{A}}=-4\pi\sigma.$$

$$U=\Sigma\frac{\dot{A}c\dot{A}}{8\pi}-\Sigma\frac{1}{2}P\sigma \qquad T=\Sigma\frac{\dot{\mathbf{Z}}\mu\dot{\mathbf{Z}}}{8\pi}-\Sigma\frac{1}{2}\Omega\rho.$$

TABLE 37.—*Magnetic fields caused by moving electric charges.*

[*Heaviside.* (Phil. Mag. [5] XXXIX, 1889). (In Common Units.)]

146. e =moving charge.

w=velocity parallel to z.

A=vector potential of moving charge, $=\frac{e\mathbf{w}}{r}=\frac{\mathbf{\Gamma}}{r}$ for $\mu_o=1$.

$$\mathbf{H}=\text{magnetic force} \quad =\text{curl } \mathbf{A}=-\frac{d\mathbf{A}}{dh}=-\frac{d\mathbf{A}}{dr}\sin\theta$$

$$=\frac{e\mathbf{w}\nu}{r^2} \quad =c\mathbf{E}\mathbf{w}\nu.$$

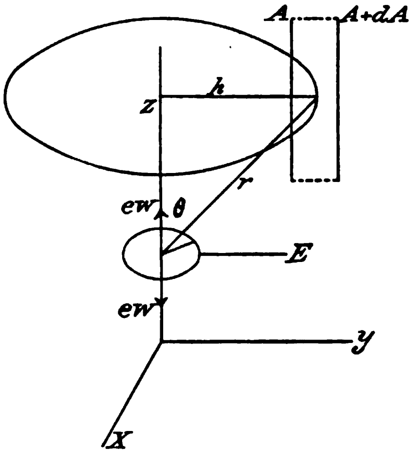

CHART 34.—Vector potential relations.

$\mathbf{H}_o$=any external magnetic field through which it moves.

$\mathbf{A}_o$=any vector whose curl$=\mu_o\mathbf{H}_o$

It has no divergence.

$\mathbf{\Gamma}$=current density of the moving system, a small charged sphere of radius a. $\mathbf{\Gamma}=e\mathbf{w}$.

The polar part of $\mathbf{\Gamma}$ contributes nothing.

Ψ_o=scalar potential of electric forces not due to $\mathbf{A}_o$.

E=intensity of radial electric force terminating on a small sphere, a.

c=permittivity (electric). μ_o=inductivity (magnetic) of the medium.

v=velocity of propagation. $\mu_o c v^2=1$. $\frac{w}{v}$ is assumed small.

147. 1. A small charged sphere moves parallel to z.

Electric force $\quad c\mathbf{E}=-e\nabla\Psi_o =\frac{e}{r^2}.$

Magnetic force $\quad \mathbf{H}=\frac{e\mathbf{w}\sin\theta}{r^2} =c\mathbf{E}\mathbf{w}\nu. \qquad \sin\theta=\nu$
$\cos\theta=\mu$

Magnetic energy $T=\Sigma\frac{1}{2}\mathbf{A}\boldsymbol{\Gamma} \quad =\Sigma\mu_o\frac{\mathbf{H}^2}{8\pi} \quad =\frac{\mu_o e^2\mathbf{w}^2}{8\pi}\int\int\int\frac{\nu^2}{r^2}dr\,d\mu\,d\lambda=\frac{\mu_o e^2\mathbf{w}^2}{3a}.$

Mutual energy of the moving charges and any external field. $M=\Sigma\frac{\mu_o\mathbf{H}_o\mathbf{H}}{4\pi}=\Sigma\mathbf{A}_o\boldsymbol{\Gamma}=\mathbf{A}e\mathbf{w}.$

Mechanical force on moving charge. $\mathbf{F}$=vector product of moment of convection current and induction of the external field.

$$=\mu_o e\,V\mathbf{w}\mathbf{H}_o=-e\frac{d\mathbf{A}_o}{dt} \quad \text{(Lagrangian Eqn. of motion).}$$

148. 2. When the external field is another moving charge.

$\mathbf{A}_o$=the vector potential of the current in the second moving system (having no divergence).

$\mathbf{A}_1$=the vector potential of the convection current$=\frac{\mu_o e\mathbf{w}}{r}$.

$\mathbf{A}_2$=the vector potential of the corresponding displacement current

$$=-\frac{1}{2r}\mu_o ew\nabla\frac{dr}{ds}.$$

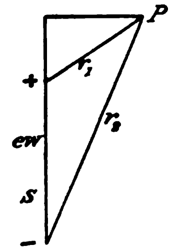

CHART 35.—Moving charge and an external point.

$$\mathbf{A}=\mathbf{A}_1+\mathbf{A}_2=\mu_o\frac{e}{r}\left(\mathbf{w}-\tfrac{1}{2}w\nabla\frac{dr}{ds}\right)$$

$$M=\mu_o e_1 e_2\left(\mathbf{w}_1\mathbf{w}_2-\tfrac{1}{2}\,w_1w_2\frac{d^2r}{ds_1ds_2}\right) \qquad w_1w_2=\text{velocity of motion in two directions.}$$

$$=\frac{\mu_o e_1 e_2 w_1 w_2}{r}\left(\cos\varepsilon+\frac{1}{2}\,\frac{d^2r}{ds_1ds_2}\right) \quad \text{(German form)} \quad \varepsilon=\text{angle between } w_1w_2.$$

$$=\frac{\mu_o e_1 e_2 w_1 w_2}{2r}(2l_1l_2+m_1m_2+n_1n_2) \quad \text{Direction cosines of } w_1w_2.$$

$\mathbf{F}_1=\mu_o e_1\,V\mathbf{w}_1\mathbf{H}_2.$ $\quad \mathbf{F}_2=\mu_o e_2\,V\mathbf{w}_2\mathbf{H}_1$, when speeds are constant.

149. 3. Electromagnetic effects of a charge moving in any way.

$w<v$ the velocity of light.

Second circuital law $-\text{curl } \mathbf{E}=\mu_o\frac{d\mathbf{H}}{dt}.$

Maxwell's law $\mathbf{J}=\mathbf{C}+\frac{d\mathbf{D}}{dt}+\rho\mathbf{w}.$ True current$=\begin{cases}\text{Currents of} \\ \text{conduction} \; + \\ \text{displacement}+ \\ \text{convection.}\end{cases}$

First circuital law Curl $\mathbf{H}=c\frac{d\mathbf{E}}{dt}+4\pi\rho\mathbf{w}$ in a nonconducting dielectric.

Electrification $\frac{1}{v^2}\frac{d^2\mathbf{H}}{dt^2}-\nabla^2\mathbf{H}=\text{curl } 4\pi\rho\mathbf{w}.$ Eliminating $\mathbf{E}$, we have,

Impressed force $\frac{1}{v^2}\frac{d^2\mathbf{H}}{dt^2}-\nabla^2\mathbf{H}=\text{curl } c\frac{d\mathbf{e}}{dt}.$ Since $\rho\mathbf{w}$ becomes $\frac{c}{4\pi}\frac{d\mathbf{e}}{dt}$,

$\frac{1}{v^2}\frac{d^2\mathbf{A}}{dt^2}-\nabla^2\mathbf{A}=4\pi\rho\mathbf{w}.$ Since $\mathbf{H}=\text{curl } \mathbf{A}$,

Vector potential $\mathbf{A}_o=\frac{4\pi\rho\mathbf{w}}{-\nabla^2}=\Sigma\frac{\rho\mathbf{w}}{r}.$

$$\mathbf{A}=\left(1+\frac{1}{v^2}\frac{d^2}{dt^2}\cdot\nabla^2+\frac{1}{v^4}\cdot\frac{d^4}{dt^4}\nabla^4+\;.\;.\;.\right)\mathbf{A}_o.$$

150. 4. Motion of electrification parallel to the z—axis.

One charge at the point. $\mathbf{w} \;.\; \mathbf{A}_o \;.\; \mathbf{A}$ are all parallel to z.

$\mathbf{A}_o = \frac{e\mathbf{w}}{r}$ $\mathbf{E}$ is radial ; $\mathbf{H}$ is in circles around z.

$$\mathbf{A} = e\,(1+\frac{1}{v^2}\frac{d^2}{dt^2}\cdot\nabla^2+\frac{1}{v^4}\frac{d^4}{dt^4}\Delta^4+\;\cdot\;\cdot\;)\frac{\mathbf{w}}{r} \text{ at distance } r \text{ from } e.$$

$$=\frac{e\mathbf{w}}{r}\left[1+\frac{w^2}{v^2}\cdot\frac{\nu^2}{2}(1+\frac{w^2}{v^2}\frac{3}{4}\nu^2(1+\frac{w^2}{v^2}\frac{5}{6}\nu^2(1+\;\cdot\;\cdot\;\right]=\frac{ew}{r}\left(1-\frac{w^2\nu^2}{v^2}\right)^{-\frac{1}{2}}$$

$$\mathbf{H}=-\frac{d\mathbf{A}}{dh}=-\nu\frac{d\mathbf{A}}{dr}+\frac{\mu\nu}{r}\frac{d\mathbf{A}}{d\mu}=\frac{e\mathbf{w}\nu}{r^2}\left(1+\mu\frac{d}{d\mu}\right)\left(1-\frac{w^2}{v^2}\nu^2\right)^{-\frac{1}{2}}$$

$$c\mathbf{E}=\frac{e}{r^2}\,\frac{1-\frac{w^2}{v^2}}{\left(1-\frac{w^2\nu^2}{v^2}\right)^{3/2}}. \qquad \mathbf{H}=c\mathbf{E}\mathbf{w}\nu=\frac{e\mathbf{w}}{r^2}\nu.$$

a. As the speed w increases the electro-magnetic field concentrates itself more and more about the equatorial plane $\theta=90^\circ$. To give an idea of the accumulation, let $\frac{w^2}{v^2}=.99$; then $c\mathbf{E}=\frac{1}{100}$ of the normal value of $\frac{e}{r^2}$ at the pole, and 10 times the normal value at the equator. The latitude where the value is normal is given by $\nu=\sin\,\theta=\frac{v}{w}\left[1-(1-\frac{w^2}{v^2})^{2/3}\right]^{1/2}$.

b. When $w=v$, the velocity of light, the solution is a plane electro-magnetic wave in the equatorial plane, $\mathbf{E}$ and $\mathbf{H}$ being zero everywhere else.

151. 5. Charge of linear density e distributed along a straight line and moving in its own direction.

Make the medium conduct electrically and magnetically, with equal rates of subsidence, ε^{-pt} diminishing to zero.

R=resistance; L=inductance; K=leakage-conductance; S=permittance; C=current; V_1=potential difference, that is transverse *E. M. F.* from wire to wire, and not the electrostatic difference of potential.

$$\mathbf{H}=c\mathbf{E}\;v=\frac{2e}{r}\cdot v.$$

$$-\frac{dV_1}{dz}=\left(R+L\frac{d}{dt}\right)C. \qquad -\frac{dC}{dz}=\left(K+S\frac{d}{dt}\right)V_1.$$

$\mathbf{E}_1=z$-component of $\mathbf{E}$. $\mathbf{E}_2=h$-component of $\mathbf{E}$.

$$\frac{1}{h}\cdot\frac{d}{dh}(h\mathbf{H})=-cw\frac{d\mathbf{E}_1}{dz}. \qquad -\frac{d\mathbf{H}}{dz}=-cw\frac{d\mathbf{E}_2}{dz}.$$

$$\mathbf{H}=cw\,\mathbf{E}_2.$$

$$\frac{d\mathbf{E}_1}{dh}-\frac{d\mathbf{E}_2}{dz}=-\mu_o w\frac{d\mathbf{H}}{dz}. \qquad \frac{d\mathbf{E}_1}{dh}=\left(1-\frac{w^2}{v^2}\right)\frac{d\mathbf{E}_2}{dz}.$$

The displacement outward through any spherical surface with charge e at the center $=e$.

152. 6. Electrification parallel to z; speed w parallel to z; e is any function of z.

If $w=v$, $\mathbf{E}_1=0$ parallel to z, $\mathbf{E}_2=\mu v\mathbf{H}=\mathbf{E}$ perpendicular to z,

$$\frac{1}{h}\frac{d}{dh}(h\mathbf{H})=0.$$

If the electrification is on the axis z.

$$\frac{\mathbf{E}}{\mu v}=\mathbf{H}=\frac{2ev}{r}.$$

153. 7. Perfectly conducting sphere of radius a and charge e moving steadily along z at the speed w. $r=a$. $w<v$.

$$U=\text{Total electric energy}=\frac{e^2}{2ca}\cdot\frac{1-\frac{w^2}{v^2}}{4}\left[1+\frac{\frac{3}{2}}{1-\frac{w^2}{v^2}}+\frac{\frac{3}{2}\tan^{-1}\frac{w}{v}\left(1-\frac{w^2}{v^2}\right)^{-\frac{1}{2}}}{\frac{w}{v}\left(1-\frac{w^2}{v^2}\right)^{\frac{3}{2}}}\right]$$

$$T=\text{Total magnetic energy}=\frac{e^2}{2ca}\cdot\frac{1-\frac{w^2}{v^2}}{4}\left[1+\frac{2\frac{w^2}{v^2}-\frac{1}{2}}{1-\frac{w^2}{v^2}}+\frac{\left(2\frac{w^2}{v^2}-\frac{1}{2}\right)\tan^{-1}\frac{w}{v}\left(1-\frac{w^2}{v^2}\right)^{-\frac{1}{2}}}{\frac{w}{v}\left(1-\frac{w^2}{v^2}\right)^{\frac{3}{2}}}\right]$$

154. 8. Case when $w>v$. Charge moves with velocity greater than light.

1. There is no disturbance in front of the charge.
2. Conical wave surfaces of angle, $\sin\beta=\frac{v}{w}$, trail behind.

Compare the original paper for this important and difficult case.

155. 9. Straight line changed to linear density e and moving in its own line.

$$H=-\frac{dA}{dh}.$$

At point P. $A=ew\log\left(\frac{r_1}{r_2}\cdot\frac{w_1+\left(1-\nu_1^2\frac{w^2}{v^2}\right)^{\frac{1}{2}}}{w_2+\left(1-\nu_2^2\frac{w^2}{v^2}\right)^{\frac{1}{2}}}\right)$

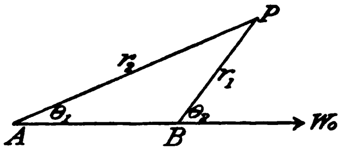

CHART 36.—Moving charged line and external point.

$$H=ew\left(1-\frac{w^2}{v^2}\right)\left[\frac{\nu_1}{r_1\left(1-\nu_1^2\frac{w^2}{v^2}\right)+r_1\mu_1\left(1-\nu_1^2\frac{w^2}{v^2}\right)^{\frac{1}{2}}}-\text{same function of } r_2\mu_2\nu_2.\right]$$

Where $\nu=\sin\theta$ and $\mu=\cos\theta$.

When P is vertically over B, and A is at an infinite distance, $H=\frac{ew}{h}$.

This is one-half the value due to an infinitely long straight current ew.

If $w=v$, $H=0$ unless $\nu_1=1$.

If P is to the left of B we must add the electrification which is ahead of P.

When P is in the middle of an infinitely long line, $H=2\frac{ew}{h}$.

156. 10. Straight line moving perpendicular to its length.

$$A=\frac{ew}{\left(1-\frac{w^2}{v^2}\right)^{\frac{1}{2}}}\log\frac{x_1+\left[x_1^2+y^2+z^2\left(1-\frac{w^2}{v^2}\right)^{-1}\right]^{\frac{1}{2}}}{x_2+\left[x_2^2+y^2+z^2\left(1-\frac{w^2}{v^2}\right)^{-1}\right]^{\frac{1}{2}}}.$$

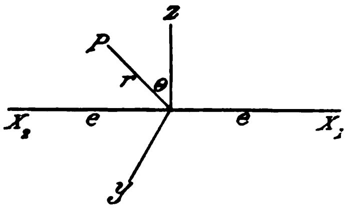

Chart 37.—Moving perpendicular to its length.

When x_1x_2 is infinite,

$$cE=\frac{2e}{r}\frac{\left(1-\frac{w^2}{v^2}\right)^{\frac{1}{2}}}{\left(1-\nu^2\frac{w^2}{v^2}\right)}. \qquad H=cEw\nu.$$

E is radial to line.
H is parallel to line.

Terminating the field internally at $r=a$ we have the case of a charged cylinder moving perpendicular to its length. When $w=v$, E and H disappear everywhere except on the plane $\theta=90°$.

157. 11. Plane charged to density e and moving perpendicular to itself.

$$H=\frac{ew}{\left(1-\frac{w^2}{v^2}\right)^{\frac{1}{2}}}\log\frac{r_1^2-y_1^2\frac{w^2}{v^2}}{r_2^2-y_2^2\frac{w^2}{v^2}}$$

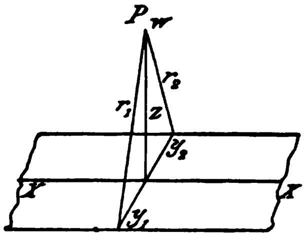

Chart 38.—Charged plane moving perpendicular to itself.

When P is equidistant from the edges $r_1=r_2$, $H=0$.
There is no H due to an infinitely large plane charged e.
The displacement current is the negative of the convection current at the same place and there is no true current.
$E_1=z$—component of E; E_2=component parallel to the plane.

$$cE_1=2e\left[\tan^{-1}\frac{y_1}{z}\left(1-\frac{w^2}{v^2}\right)^{\frac{1}{2}}-\tan^{-1}\frac{y_2}{z}\left(1-\frac{w^2}{v^2}\right)^{\frac{1}{2}}\right]. \qquad E_2=\frac{H}{cw}.$$

When the plane is infinite, $H=0$, $E_2=0$; $cE_1=cE=2\pi e$.

158. 12. Charged plane moving in its own plane.

$$H=2ew\left[\tan^{-1}\frac{z}{h\left(1-\frac{w^2}{v^2}\right)^{\frac{1}{2}}}\right]_{z_1}^{z_2}.$$

z_1z_2 are the extreme values of z measured parallel to the breadth of the plane.

$+H=2\pi ew$ above plane if infinite; $-H=2\pi ew$ below plane.
Compare J. J. Thomson, Phil., May, July, 1889.

Table 38.—*The conduction of electricity through gases by charged ions.*

J. J. THOMPSON'S SOLUTION FOR A STEADY STATE OF THE GAS.

159. q=the number of positive and negative ions each, produced in unit volume and in unit time.
n_1=the number of positive ions per unit volume.
n_2=the number of negative ions per unit volume.
$n_1 n_2$ is proportional to the number of collisions in the unit time.
$\alpha n_1 n_2$=the number that disappear by recombination to form an electrically neutral system.
e=the electric charge carried by each ion.
X=the electric force parallel to x, along the line of discharge.
$k_1 X$=the velocity of the positive ion.
$k_2 X$=the velocity of the negative ion; equal to, greater, or much greater than that of the positive ions.
i=the movement of the ions under the electric forces, or the current through the unit area of the gas, neglecting diffusion not due to the electric field.

160. Electric slope. $\frac{dX}{dx}=4\pi\ (n_1-n_2)\ e=4\pi\times$ volume density of electrification.

161. Movement. $i=k_1 n_1 eX+k_2 n_2 eX.$ Constant in steady state of gas.

162. Pos. and neg. vol. density. $n_1 e=\frac{1}{k_1+k_2}\left(\frac{i}{X}+\frac{k_2}{4\pi}\frac{dX}{dx}\right).$ $n_2 e=\frac{1}{k_1+k_2}\left(\frac{i}{X}-\frac{k_1}{4\pi}\frac{dX}{dx}\right).$

163. Excess of ionization above recombination. $\frac{d}{dx}(k_1 n_1 X)=q-\alpha n_1 n_2.$ $-\frac{d}{dx}(k_2 n_2 X)=q-\alpha n_1 n_2.$

164. General equation.

$$\frac{1}{4\pi e}\cdot\frac{k_1 k_2}{k_1+k_2}\cdot\frac{d}{dx}\left(X\frac{dX}{dx}\right).$$
$$=q-\frac{\alpha}{X^2 e^2\ (k_1+k_2)^2}\left(i+\frac{k_2}{4\pi}\dot{X}\frac{dX}{dx}\right)\left(i-\frac{k_1}{4\pi}X\frac{dX}{dx}\right).$$

165. Auxiliaries. $X^2=2y;$ $\frac{dy}{dx}=p;$ Take q=const; $k_1=k_2=k;$ Integrate.

166. Solution. $\frac{k^2}{16\pi^2}p^2-i^2=\frac{qek}{\pi\ (1-\frac{\alpha}{8\pi ek})}y+C\,(2y)^{\frac{\alpha}{8\pi ek}}$ C=const. of integration.

The steady state is unstable and breaks up into luminous striæ.

MODIFIED EQUATION BY J. H. JEANS.

Introduce expressions for new forces of repulsion, elasticity, etc., such that q and α are functions of X at the point measured; q and α are single valued functions of y and p.

167. Thomson's equation. $\frac{1}{4\pi e}\cdot\frac{k_1 k_2}{k_1+k_2}\frac{d^2y}{dx^2}=q-\frac{\alpha}{2ye^2\ (k_1+k_2)}\left(i+\frac{k_2}{4\pi}p\right)\left(i-\frac{k_1}{4\pi}p\right).$

168. Jeans' equation. $\frac{1}{4\pi e}\cdot\frac{k_1 k_2}{k_1+k_2}p\frac{dp}{dy}=q+\frac{\alpha k_1 k_2}{32\pi^2 e^2\ (k_1+k_2)^2 y}\left[p^2-4\pi i\left(\frac{1}{k_1}-\frac{1}{k_2}\right)p-\frac{16\pi^2 i^2}{k_1 k_2}\right].$

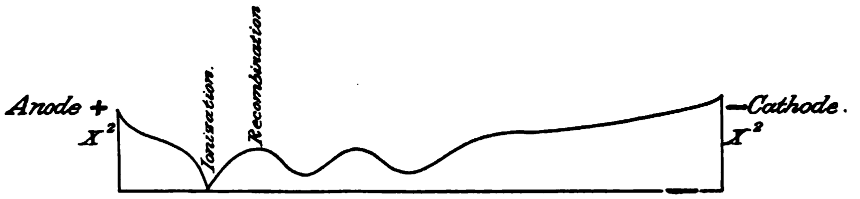

Chart 39.—The minima and maxima of ionization.
References: J. J. Thomson, Phil. Mag., March, 1899; J. H. Jeans, Phil. Mag., March, 1900

Ionization occurs at the minima, and recombination at the maxima of curve.

Thomson's equation gives sharp and Jeans' rounded minima.

Since luminous striæ occur at the places of recombination, it is probable that the visible coronal and auroral rays mark the places of recombination of the ions, and the dark interspaces those of ionization at the sun and earth, respectively. There is an excessive density of ions in the luminous striæ.

THEORY OF THE NEGATIVE GLOW, THE DARK SPACE, AND THE POSITIVE COLUMN.

[J. J. Thomson, Phil. Mag., April, 1901.]

169. λ=mean free path of a corpuscle.

$Xe\lambda$=work done on it by the electric field=mean kinetic energy acquired.

f=fraction of whole number of collisions leading to ionization.

β=fraction of collisions leaving corpuscles sticking to molecules.

u=average velocity of negative corpuscle=$k_2\sqrt{X}$ (instead of k_2X).

v= " " " positive corpuscle=$k_1\sqrt{X}$ (instead of k_1X).

n_2=number of negative corpuscles.

n_1= " " positive " .

Notation changes m to n_1, n to n_2, k_1 to k_2, k_2 to k_1 to reduce this paper to the preceding.

$\frac{\lambda}{u}$=the interval between two collisions.

$n_2\frac{u}{\lambda}$=total number of collisions in unit time per unit volume.

$n_2\frac{u}{\lambda}f(Xe\lambda)$=number of ions produced in unit volume per second.

$n_2\frac{u}{\lambda}\beta$ =number of ions which disappear in unit volume per second.

$\frac{n_2u}{\lambda}\left[f(Xe\lambda)-\beta\right]$=rate at which the ions increase per unit volume.

The axis x is positive from the cathode to the anode.

The electric force X is directed from the anode to the cathode.

170. $$\frac{dn_2}{dt}+\frac{d(n_2u)}{dx}=\frac{n_2u}{\lambda}\left[f(Xe\lambda)-\beta\right].$$ $\frac{dn_2}{dt}=0$ for steady state.

$\frac{d(n_2u)}{dx}=0$ for uniform column.

171. $$i=n_1v+n_2u=n_1k_1\sqrt{X}+n_2k_2\sqrt{X}.$$

This differs from 161 by assuming the velocity proportional to $\sqrt{X}$ instead of to X, and making $e=1$.

Since kinetic energy=$X\lambda=\frac{1}{2}mv^2$, $v=\sqrt{\frac{2\lambda}{m}}\sqrt{X}=k_1\sqrt{X}$.

172. $$\frac{dX}{dx}=-4\pi\rho=-4\pi\,(n_1-n_2)e\,,\quad \rho=\text{volume density of electrification.}$$

173. $$n_2u=\frac{n_2k_2\sqrt{X}}{k_1+k_2}=\frac{k_2i}{k_1+k_2}+\frac{k_1k_2}{4\pi e}\cdot\frac{\sqrt{X}}{k_1+k_2}\cdot\frac{dX}{dx}.$$

174. $$\frac{d(n_2u)}{dx}=\frac{k_1k_2}{4\pi e}\cdot\frac{2}{3}\frac{d^2X^{3/2}}{dx^2}=\frac{n_2u}{\lambda}\left[f(Xe\lambda)-\beta\right].$$

$$=\left[\frac{k_2}{k_1+k_2}\frac{i}{\lambda}+\frac{2}{3}\frac{k_1k_2}{4\pi e\lambda(k_1+k_2)}\frac{dX^{3/2}}{dx}\right]\left[f(Xe\lambda)-\beta\right].$$

175. When $f(Xe\lambda)-\beta$ is positive, $X>X_0$. X_0=value of X in the uniform positive column.

" " $\frac{d^2X^{3/2}}{dx^2}$ is positive.

" " graph of $X^{3/2}$ is convex to axis x.

Rule: $X^{3/2}$ is $\begin{Bmatrix}\text{convex}\\ \text{concave}\end{Bmatrix}$ to axis x according as $\begin{Bmatrix}X>X_0.\\ X<X_0.\end{Bmatrix}$

The electric force is $\begin{Bmatrix}\text{increasing}\\ \text{diminishing}\end{Bmatrix}$ toward the anode according to excess of $\begin{Bmatrix}\text{positive}\\ \text{negative}\end{Bmatrix}$ ions at the point of observation.

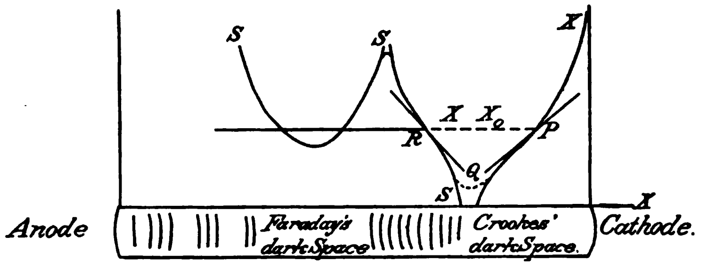

CHART 40.—Critical points on the electric force in discharge tubes.

Two cases. Tangent parallel to x, or not.

R . P=points of tangency.

Q=ionization exceeds recombination.

S . S=points of unsteadiness.

TABLE 39.—*The Zeeman effect.*

ELECTRO-MAGNETIC UNITS.

[Zeeman, Lamor, Preston, Michelson, Cornu, Lorentz, Reese.]

The general equations of motion of a particle which describes an ellipse about the axis $(l\,.\,m\,.\,n)$ under a force directed toward its center k_1^2r, with perturbing forces which rotate the ellipse in its own plane with the angular velocity ω, and oscillate the plane itself.

176.

$$\begin{array}{lllll} \text{Acceleration.} & \text{Elastic resistance.} & \text{Mechanical deflection.} & \text{Centrifugal component in plane.} & \text{Centrifugal force from component perpendicular to the plane.} \\ \ddot{x}= & -k_1^2x & +2\omega\,(n\dot{y}-m\dot{z}) & +\omega^2x & -\omega^2l\,(lx+my+nz). \\ \ddot{y}= & -k_1^2y & +2\omega\,(l\dot{z}-n\dot{x}) & +\omega^2y & -\omega^2m\,(lx+my+nz). \\ \ddot{z}= & -k_1^2z & +2\omega\,(m\dot{x}-l\dot{y}) & +\omega^2z & -\omega^2n\,(lx+my+nz). \end{array}$$

177. ω=angular velocity of the axes of the ellipse about $(l\,.\,m\,.\,n)$

The elastic resistance is directed toward the center.

The deflecting force, $2\omega\,.\,q\sin\theta$, acts perpendicular to the plane $q\,.\,(l\,.\,m\,.\,n)$ where q makes the angle θ with the axis of rotation.

The centrifugal force has a component in the plane of rotation and another perpendicular to it; they produce a rotation of the apsides and an oscillation of the plane, if periodic.

Compare equations of the International Cloud Report (155), (167), (181), (228), etc.

All these motions combined, if periodic, produce the entire series of the multiple lines of the Zeeman effect.

If the velocity q and also the axis $(l\,.\,m\,.\,n)$ coincide with z, since $(l\,.\,m\,.\,n)=(0\,.\,0\,.\,1)$ we have with and without centrifugal force.

178.

$$\begin{array}{ll} \ddot{x}=-(k_1^2-\omega_3^2)x+\omega_3 2\dot{y}. & \qquad \ddot{x}=-k_1^2x+2\omega_3\dot{y}. \\ \ddot{y}=-(k_1^2-\omega_3^2)y-2\omega_3\dot{x}. & \qquad \ddot{y}=-k_1^2y-2\omega_3\dot{x}. \\ \ddot{z}=-\,k_1^2z. & \qquad \ddot{z}=-k_1^2z. \end{array}$$

179. Frequencies, Unmodified. $n=\frac{1}{T}=\frac{k_1}{2\pi}=\frac{k}{2\pi\sqrt{m}}.$ m=mass moved.

Modified. $n_1=\frac{1}{T_1}=\frac{p_1}{2\pi}=\frac{k}{2\pi\sqrt{m}}\left(1\mp\frac{eH}{2k\sqrt{m}}\right).$

180. The sign $-$ is for positive rotation with period less in field.
The sign $+$ is for positive rotation with period greater in field.
Periodic times, Unmodified$=T;$ Modified$=T_1$.

181. Ratio $\frac{\varDelta T}{T}=\frac{T\frac{eH}{2k\sqrt{m}}}{T}=\frac{e}{m}\cdot\frac{HT}{4\pi}.$

All motions of the ion can be resolved into linear vibrations parallel to the lines of torce with two circular vibrations, right-handed and left-handed, perpendicular to the lines of force.

182. *Solution.* $(x\,.\,y\,.\,z)=(x_o\,.\,y_o\,.\,z_o)e^{ipt}=(x_o\,.\,y_o\,.\,z_o)e^{st}.$ Take $\omega^2=0$.
If the unmodified principal vibration is a linear oscillation parallel to z.

183. $(x\,.\,y)=(x_o\,.\,y_o)e^{ipt}\quad=(x_o\,.\,y_o)e^{st}.$

$$s^2x_o=-k_1^2x_o+2\omega sy_o.$$

$$s^2y_o=-k_1^2y_o-2\omega sx_o.$$

184. If $\omega=0$ $\quad s^2=-p^2=-k_1^2\qquad p=k_1\qquad s=ip=ik_1.$

185. If ω is not $=0$ $\quad(p^2-k_1^2)^3-b^2p^2(p^2-k_1^2)\quad=0\qquad 2\omega=b.$

$$(p^2-k_1^2)\Big[(p^2-k_1^2)^2-b^2p^2)=0.$$

$$p=k_1.$$

$$p^2-k_1^2=\pm bp.$$

$$p=k_1+\frac{b^2}{8k}\pm\tfrac{1}{2}b\qquad\text{Take } b^2=0,\qquad k_1=\frac{k}{\sqrt{m}},\qquad b=\frac{eH}{m}=2\omega.$$

186. $p=k_1\pm\omega=\frac{k}{\sqrt{m}}\pm\frac{eH}{2m}$

The original periodic motion, $p=k_1$, is modified into a doubly periodic motion $p+\omega$ and $p-\omega$.

Hence, the magnetic force H, acting on $\frac{e}{m}$ moving in an ellipse, rotates the ellipse with the angular velocity $2\omega=\frac{eH}{m}$.

The motion is unmodified.

187. The rotating ellipse. $x=a\cos k_1t.$ $y=b\sin k_1t.$ Where $k_1=2\pi n$.

The motion is modified by the angular velocity ω.

188. $\begin{cases}x=a\cos k_1t\cos\omega t-b\sin k_1t\sin\omega t.\\ y=a\cos k_1t\sin\omega t+b\sin k_1t\cos\omega t.\end{cases}$ By composition,

189. $\begin{cases}x=\frac{1}{2}(a+b)\cos(k_1+\omega)t+\frac{1}{2}(a-b)\cos(k_1-\omega)t=x_1+x_2.\\ y=\frac{1}{2}(a+b)\sin(k_1+\omega)t-\frac{1}{2}(a-b)\sin(k_1-\omega)t=y_1+y_2.\end{cases}$

The resultant motion is equivalent to two opposite circular motions of frequencies $n+n_1$ and $n-n_1$.

190. The term in z may be taken doubly periodic:

$$z=a \sin n_1 t \sin k_1 t=\frac{a}{2}\Big[\cos (k_1-n_1)t-\cos (k_1+n_1)t\Big].$$

This represents two vibrations of equal amplitude and frequencies, $\frac{k_1-n_1}{2\pi}$ or $\frac{k_1+n_1}{2\pi}$, required for the quartet.

The sextet and other complex vibrations are formed by evaluation of the perturbing forces which were neglected above in terms of ω^2.

Thus the rotation of the orbits of the triplets around the line of apsides in addition converts the group into a sextet. Variations of this principle contribute to form the several types of widenings and groupings that have been observed.

191. The circular or elliptical motions of the ion m is accelerated by adding the component of the circular magnetic rotation.

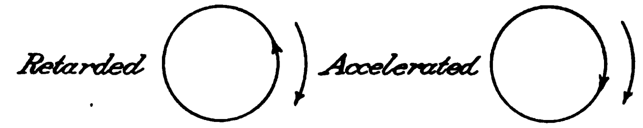

CHART 41.—Retardation and acceleration of a rotating ion.

192. The single spectrum line is split up into a triplet when viewed *across* the lines of the magnetic field and each is plane polarized, A and C parallel to the field and B at right angles to it. A Nichol prism parallel to the field cuts out A and C; at right angles to the field it cuts out B. The line B is twice as bright as A or C.

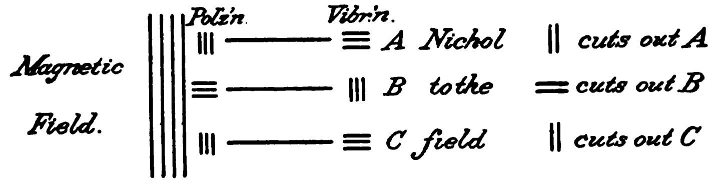

CHART 42.—Polarization viewed across a magnetic field.

193. The single spectrum line is converted into a doublet when viewed *along* the magnetic field. One component is circularly polarized left-handed; the other is circularly polarized right-handed; the missing middle line has vibrations seen end on which are indistinguishable.

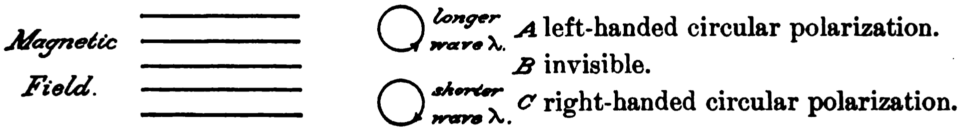
Magnetic
Field.
longer wave λ.
A left-handed circular polarization.
B invisible.
shorter wave λ.
C right-handed circular polarization.

CHART 43.—Polarization viewed along a magnetic field.

194. The ratio $\frac{e}{m}$ is of the order 10^7 electro-magnetic C.G.S. units.

The mass of the ion is $\frac{1}{1000}$ the mass of the atom. There are probably 1,000 electrons in an atom. The total structure of the molecule has the ions vibrating about its center in circular, elliptical, or more complex orbits which are disturbed by immersion in a magnetic field in accordance with these mathematical principles.

References.—				
Zeeman.	Phil. Mag.	Mar., 1897;	Astrophys.	Jan., 1899.
Lamor.	Phil. Mag.	Dec., 1897.		
Preston.	Phil. Mag.	Apr., 1898;	Phil. Mag.	Feb., 1899.
Michelson.	Astrophys.	June, 1897;	Astrophys.	Feb., 1898.
Cornu.	Astrophys.	Dec., 1897;	Astrophys.	Mar., 1898.
Lorentz.	Astrophys.	Jan., 1899.		
Reese.	Astrophys.	June, 1898;	Astrophys.	Sept., 1900.

TABLE 40.—*Shifting and broadening of spectrum lines.*

[Jewell—Humphreys—Mohler—Wilson—Wilsing—Godfrey.]

195. General law.

$$\triangle\lambda = a\,.\,b\,.\,\lambda\,(B-B_o).$$

$$= \frac{\alpha\sqrt[3]{v}}{T_m}\left\{\begin{matrix}1\\2\\3\end{matrix}\right\}.\,\lambda\,(B-B_o).$$

$$= \frac{\alpha\sqrt[3]{\dfrac{m}{\rho}}}{T_m}\left\{\begin{matrix}1\\2\\3\end{matrix}\right\}.\,\lambda\,(B-B_o).$$

λ=wave length.
α=coef. of linear expansion.
v=atomic volume.
m= " mass.
ρ= " density.
T_m=absolute temperature of the melting point.
B=barometric pressure.
b is proportional to the Mendeljeff series:
1=Principal.
2=First subordinate.
3=Second subordinate.

196. Shift in the different orders of spectrum.

$$\frac{\lambda\,.\,\text{3d Spect}}{\lambda\,.\,\text{2d Spect}} = \frac{2}{3};\qquad \frac{\triangle\lambda\,.\,\text{3d Spect}}{\triangle\lambda\,.\,\text{2d Spect}} = \frac{3}{2}.$$

$$\lambda\,.\,\triangle\lambda\,.\,\text{2d} = \lambda\,.\,\triangle\lambda\,.\,\text{3d} = \text{Const.}$$

197. Constant product.

$$T_m\,.\,\alpha\,.\,\sqrt[3]{v} = T_m\,.\,\alpha\,.\,\sqrt[3]{\frac{m}{\rho}} = 48600.$$

Reducing to wave length 4,000 and 12 atmospheres.

198. The average shift. $\triangle\lambda$=0.010 Ångström unit per atmosphere toward the red.

It varies for different elements.

199. Physical conditions.

	An increase of		
	Temperature.	Density.	*Pressure.*
Increases the	Number of lines and intensity.	Width symmetrically or unsymmetrically.	Shift or change in wave length.

Hence the Michelson standard wave lengths, cadmium red, green, blue, are essentially *relative.* They differ .208 .173 .186 Ångst. U. from Rowland's.

THEORETICAL EXPLANATIONS OF THE EFFECT.

200. General view. v Lommel: The damping is due to resistance of medium.

Wilsing's extension: In addition, the moment of inertia is increased by the internal friction of the medium as Bessel and Stokes show in pendulum vibrations.

Godfrey: Gives the analogue of a vibrating plate.

General equation. v Lommel: A damped simple harmonic vibration subject to the periodic impulse $-F\sin qt$, where x= distance of the moving m from point of equilibrium.

201. 1st form.

$$m\frac{d^2x}{dt^2}+K\frac{dx}{dt}+Ax+Bx^2+Cx^3+\;.\;.\;.\;+F\sin qt=0.$$

202. 2d form.

$$\frac{d^2x}{dt^2}+\frac{K}{m}\frac{dx}{dt}+\frac{A}{m}x+\frac{B}{m}x^2+\frac{C}{m}x^3+\;.\;.\;.\;+\frac{F}{m}\sin qt=0.$$

203. 3d form.

$$\frac{d^2x}{dt^2}+2k\frac{dx}{dt}+p^2x+b\epsilon x^2+c\epsilon^2x^3+\;.\;.\;.\;+f\sin qt=0.$$

204. Coefficients. k=damping; $b\epsilon$ and $c\epsilon^2$=fluorescence.

f=amplitude of the excitant vibration of period $\frac{\pi}{q}$.

205. Periods.

$\frac{\pi}{p}$=period of undamped vibration.

$\frac{\pi}{r}=\frac{\pi}{\sqrt{p^2-k^2}}$=damped vibration.

$\frac{\pi}{q}$=period of excitant vibration.

$\frac{\pi}{\mu_0}$=period of maximum intensity vibration.

206. Two physical theories: Dynamical, with changes in molecular or atomic vibrations.

Electromagnetic, with changes in the vibrations of electric charges and specific inductive capacity of the medium.

207. Wilsing's extension.

$$\frac{d^2x}{dt^2}+\frac{2k}{1+\gamma}\frac{dx}{dt}+\frac{p^2}{1+\gamma}x \quad + \ldots \qquad +\frac{f}{1+\gamma}\sin qt=0$$

208. Acoustical analogue.
Rayleigh-Godfrey.

$$\frac{d^2x}{dt^2}+\frac{\frac{\rho\pi p^2R^3}{3M}}{1+\frac{8\rho R^3}{3M}}+\frac{p^2}{1+\frac{8\rho R^3}{3M}}+\ldots \qquad =0$$

$$\gamma=\frac{8\rho R^3}{3M} \qquad 2k=\frac{\rho\pi p^2R^3}{3M}$$

ρ=density of air.
M=mass of disk.
c=velocity of sound.
R=radius of disk.
λ=wave length of emitted rays.

209. Solution.

(v. Lommel:) $x=M\sin(qt-\alpha)+Ne^{kt}\sin(rt+\psi)$.

(Wilsing:) $x=M\sin(qt-\alpha)+Ne^{-\frac{kt}{1+\gamma}}\sin(rt+\psi)$.

210. Molecular absorption.

(v. Lommel:) $\Delta=\frac{mf^2\sin^2\alpha}{16k^2}$; $\quad \tan\alpha=\frac{2kq}{p^2-q^2}$.

If $k_1=\frac{k}{1+\gamma}$, $f_1=\frac{f}{1+\gamma}$, $p_1^2=\frac{p^2}{1+\gamma}$, γ=damping coefficient.

(Wilsing:) $\Delta=\frac{mf_1^2}{16k_1^2}\sin^2\alpha$; $\quad \tan\alpha=\frac{2k_1q}{p_1^2-q^2}$.

$$d\Delta=\frac{m}{2}\left(\int_0^t\left(\frac{dx}{dt}\right)^2dt-\left\{\int_0^t\left(\frac{dx}{dt}\right)^2dt\right\}_{f=0}\right).$$

211. Maximum absorption or place of brightest line.

When $q^2=p^2$ by v. Lommel's theory.

When $q^2=p_1^2=\frac{p^2}{1+\gamma}$ by Wilsing's theory.

The relative displacement toward the red

$$\frac{\pi}{p_1}-\frac{\pi}{p}=\frac{\pi\gamma}{2p}$$

If γ^2 and $\left(\frac{k_1}{p}\right)^2$ can be neglected, the bright lines and the absorption lines are shifted equally.

212. Noncoincidence of the max. with the main vibration.

$$e^{-k_1t}\sin r_1t=\frac{4k_1r_1}{\pi}\int_0^\infty\frac{\mu}{(k_1^2+r_1^2+\mu^2)^2-4r_1^2\mu^2}\sin\mu t d\mu.$$

213. Amplitude of period $\frac{\pi}{\mu}$. $\quad f_\mu = \frac{4kr_1}{\pi}\,\frac{\mu}{(k^2+r_1^2+\mu^2)^2-4r_1^2\mu^2}$.

$\frac{\pi}{\mu_o}$ $\quad \left(\frac{dg}{d\mu}\right)_{\mu=\mu_o}=0 \qquad \mu_o^2=\tfrac{1}{3}(p_1^2-2k^2)+\tfrac{2}{3}(p_1^4-p_1^2k^2+k^4)^{1/2}$

$$\mu_o^2=r_1^2+\frac{k^4}{4p_1^2}+\ \cdot\ \cdot\ \cdot$$

$$r_1 = \sqrt{p_1^2-k_1^2}=\sqrt{\frac{p^2}{1+\gamma}-\left(\frac{k}{1+\gamma}\right)^2}, \qquad \text{If } \left(\frac{k_1}{p}\right)^2=0.$$

214. Main amplitude. $\quad f_{p1} = \frac{4kp_1}{\pi}\cdot\frac{\mu}{(p_1^2-\mu^2)^2}$.

$f^2_\mu : f^2_{p1} = I_\mu : I_{p1}$ $\quad$ Hence lines are shifted but are not perceptibly wider.

215. Electrical analogue. $\quad \triangle\lambda=\lambda_r-\lambda_p=\gamma\frac{B}{2}\cdot\lambda_r \qquad \lambda_r=4.10^{-4}\text{mm. for } \frac{\pi}{r}$

$=2.10^{-8} \qquad \lambda_p= \qquad \text{for } \frac{\pi}{p}$

$\left(\frac{k}{p}\right)^2$ vanishes for no broadening; $B=12$ atmospheres.

$\left(\frac{k}{p}\right)^2$ is sensible for fluorescence. $\quad \gamma=8.10^{-6}$

TABLE 41.—*The radiation function in the spectrum.*

[Stefan—Wien—Paschen—Nutting.]

216. General form of the function. $\quad$ 1. $J=ae^{-\frac{b}{T}}$. $\quad \lambda=$ wave length in μ.

217. For a perfect radiator. $\quad$ 2. $J=A\lambda^{-\alpha}e^{-\frac{B}{\lambda}}$. $\quad T=$ absolute temperature.
$e=$ Naperian Base.

218. Emission with single maximum and variable temperature. $\quad$ 3. $J=c_1\lambda^{-\alpha}e^{-\frac{c_2}{\lambda T}}$. . . . Wien's Formula.

219. Constants. $\quad a=A\lambda^{-\alpha}=c_1\lambda^{-\alpha}, \qquad b=\frac{B}{\lambda}=\frac{c_2}{\lambda}, \qquad \alpha=5.$

$$\left.\begin{aligned} c_1&=\frac{J_m}{T^5}(\lambda_m Te)^5=\frac{J_m}{T^5}\left(\frac{c_2e}{5}\right)^5 \\ c_2&=5\lambda_m T=5\times 2891=14455 \end{aligned}\right\}\text{Paschen.}$$

		Formula.	Energy Curves.	Isochromatic Curves.	
220. For low temperatures and long wave lengths. $T=273°$ to $750° C.$	c_1	633000	634600	631900	Watts/cm^2.
	c_1'	152290	152330	151680	$\frac{\text{Gr. Cal.}}{\text{sec}}/cm^2$.
	c_2	14455	14455	14455	
221. For high temperatures and short wave lengths. $T=750°$ to $1500° C.$	c_1'	**146030**	145870	145300	
	c_2	**14531**	14514	14520	

c_1' for low temperatures $=\frac{c_1}{4.166}$, where $\frac{\text{Gr. Cal.}}{\text{sec}}\cdot\frac{1}{cm^2}\times 4.166=\text{Watts}\cdot\frac{1}{cm^2}$.

222. Maximum emission. $\quad$ 4. $J_m=c_1\left(\frac{\alpha}{c_2e}\right)^\alpha T^\alpha=c_1\left(\frac{5}{c_2e}\right)^5T^5 \qquad =BT^5.$

223.	Maximum wave length.	5.	$\lambda_m=\frac{c_2}{\alpha T}$ $\quad=\frac{c_2}{5T}$ $\quad=\frac{A}{T}$.
224.	Total intensity of emission, which is the heat equivalent of total radiation emitted by a black body at temperature T.	6.	$J_o=\int_o^\infty J d\lambda$ $\quad=c_1c_2^{1-a}\Gamma(\alpha-1)T^{a-1}=\sigma T^4$. $=6\frac{c_1}{c_2^4}T^4$. . . . Stefan's Law. $=1.277\times10^{-12}T^4\frac{\text{Gr. Cal.}}{cm^2\text{sec}}$ $=5.32\times10^{-12}\ .\ T^4\frac{\text{Watts}}{cm^2}$.
225.	Constants. Heat equivalent of the total radiation by ideal black body at T. (A probably varies with T.)	7.	$C_1=9292\frac{\text{Gr. Cal.}}{cm^2\text{sec}}\times\mu^4=38710\frac{\text{Watts}}{cm^2}\times\mu^4$. $C_2=14455\mu\ .\ T$ degrees. $A=\lambda_m T=2891.$ $\qquad\lambda T=$constants. $B=\frac{J_m}{T^5}=2.120\times10^{-14}$.
226.	Ratio of intensities.	8.	$\frac{J}{J_m}=\left\{\frac{\lambda_m}{\lambda}e^{\frac{\lambda-\lambda_m}{\lambda}}\right\}^a$.
227.	Add a sharp maximum of constant wave length.	9.	$J=c_1(\lambda-\lambda_m)^{-a}e^{-\frac{c_2}{\lambda T}}$.
228.	Restrict to real values.	10.	$J=c_1\lambda^{-a}e^{-\frac{c_2}{\lambda T}}(\lambda-\lambda_m)^{-2}$.
229.	Add several maxima or spectral lines.	11.	$J=c_1\lambda^{-a}e^{-\frac{c_2}{\lambda T}}\Sigma_{m=1}^{m}(\lambda-\lambda_m)^{-2}$,

where $(\lambda-\lambda_m)^{-a}$ is the sharp maximum of each line, and λ . . . . λ_m include the reflection, refraction, and absorption wave lengths.

λ_m is probably dependent upon the molecular or atomic period.

Near λ_m and within a few octaves of it, emission by (11) is much less than by (3), using the same constants.

On the side of the *short* periods from λ_m (3) does not hold perfectly.

On the side of the *long* periods from λ_m the emission is like that from a black body and is given by (3).

TABLE 42.—*Heliographic positions.*

[Referred to the north side of the ecliptic.]

230. Poles. S=sun; E=earth; K=ecliptic; C=coronal axis.

231. Inclinations. I=sun's equator to ecliptic= 7° 15′.
ω=earth's equator to ecliptic=23° 27′.
(H+G)=earth's equator to sun's equator=26° 20′ (in maximum)

232. Distances. R=solar radius on photograph; R' corrected for distortion.
r=spot from center of picture; r' " " "
R''=sun's radius in the ephemeris.
ρ'=measured distance of spot from center in terms of R''.

233. Angles.
ρ=heliocentric angle of sun spot Σ from earth.
$G=EO'K$ (+ when E is east of K).
$H=KO'S$ (+ when K is east of S).
$P=SO'E$ (+ from E through east).
$\chi=P+G+H$.

O = projection of O′ on the plane through Σ.
Σ'= projection of Σ on the plane through O′.
O′= center of sun.

234. Longitudes.
$\odot$=sun's celestial.
N=sun's ascending node=73° 40′ (1850).
L=nodal heliocentric of earth $C=NO'C$.
l=nodal heliocentric of spot $\Sigma=NO'\Sigma$.
$L-l$=heliocentric of spot Σ from the central meridian$=CO'\Sigma$.
l'=heliocentric of prime meridian M from $N=NO'M$.
$L-l'$=heliocentric of center of disk O from $M=MO'O$.
$l-l'$=heliocentric of the sun spot Σ from $M=\Sigma O'M$.

235. Latitudes.
D=sun's equator to the ecliptic.
F=sun's equator to the earth's equator.

d=sun's equator to the spot Σ.

236. Time.
T=the fraction of a revolution executed by the prime meridian at a given date.
t=time from epoch. Epoch=1854—0^d.0=mean midnight Dec. 31, 1853.
κ =mean angular velocity of sun on its axis.
n=mean angular velocity of earth around sun.
$\kappa-n$=synodic angular velocity of the sun.
m=complete number of siderial rotations of the M since the epoch.

237. 1. $\tan G=\tan\omega\cos\odot$. +=east; −=west.

238. 2. $\tan H=\tan I\cos(\odot-N)$. +=east; −=west.

239. 3. $\tan L=\cos I\tan(\odot-N)$.

240. 4. $\sin D=\sin I\sin(\odot-N)$. +=north; −=south.

241. 5. $\rho'=\frac{r'}{R'}(R'')$.

242. 6. $\rho=\sin^{-1}\frac{r'}{R'}-\rho'$.

243. 7. $\sin d=\cos\rho\sin D+\sin\rho\cos D\cos\chi$.

244. 8. $\tan F=\tan\omega\sin\odot$. +=north; −=south.

245. 9. $\sin(L-l)=\sin\chi\sin\rho\sec d$.

246. 10. $T=\frac{t}{24.863}-m$.

247. 11. $l'=T\times\frac{360}{24.863}=T\times 14.4783$. (Bigelow.)

$=T\times 14.1844$. (Carrington.)

References: CARRINGTON. Observations at Redhill, London, 1863.
VERY. Astrophysics, Oct.-Dec., 1897; Jan., 1898.
BIGELOW. Weather Bureau Bulletin No. 21.
Astrophysics, Nov., 1893.

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